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THE MECHANICAL PROPERTIES OF THE 18 PER CENT NICKEL MARAGING STEELS

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THE MECHANICAL PROPERTIES OF THE 18 PER CENT NICKEL MARAGING STEELS

by

J. E. Campbell, F. J. Barone, and D. P. Moon

to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
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THE MECHANICAL PROPERTIES OF THE
18 PER CENT NICKEL MARAGING STEELS

SUMMARY

This report is intended to provide as complete a background of information on the mechanical properties of the 18 per cent nickel maraging steels as is obtainable at the present state of development of these alloys. Since the combination of tensile properties and toughness that can be obtained with the maraging steels is higher than can be achieved with other steels by simple heat treatments, there is considerable interest in using the maraging steels for critical components such as rocket motor cases, pressure vessels, and aircraft forgings. ~~Before these new alloys can be considered for such applications, considerable information on their mechanical properties must be collected~~ and ~~evaluated~~.

This report includes information on the tensile, compressive, shear, bearing, dynamic modulus, impact, bend, fatigue, creep, and rupture properties of the 18 per cent nickel maraging steels and on the effect of temperature on these properties. Data for the properties of sheet, bar, and forgings, as well as data illustrating the effect of cold rolling, variation in the heat treatment, and elevated-temperature exposure also are presented. Data on the effect of specimen orientation, which are also included, indicate that the ductility and toughness of specimens designed to evaluate the properties in the short transverse direction are somewhat lower than in the other directions.

The high strength and toughness that can be obtained in the 18 per cent nickel maraging steels make them attractive for certain critical applications that require these properties. The fabrication characteristics, weldability, and simple heat treatment are other advantages of these steels.

INTRODUCTION

The maraging steels are a class of iron-nickel-cobalt-molybdenum-titanium alloys with low carbon contents. There are four major types of maraging steels containing 15, 18, 20, and 25 per cent nickel. The 18 per cent nickel type is the most important at present because of its advantages for use in large high-strength structures including pressure vessels and large boosters. These advantages will become evident as the properties and processing of the 18 per cent nickel type are reviewed in this report.

Within the 18 per cent nickel type, there are several grades arbitrarily based on yield strength; i.e., the 200, 250, and 300 grades representing yield-strength levels of 200,000, 250,000, and 300,000 psi, respectively. In some instances, other grade designations also have been used, e.g., 180, 225, 280, and 325 grades. The actual strength level that may be achieved for a given heat of 18 per cent nickel maraging steel depends primarily on the "hardener content", that is, the amounts of titanium, molybdenum, and cobalt present in the alloy. Because of variations in the intended hardener content and "aging response", the actual properties obtained for a specified grade fall within a scatter band. The scatter bands for the various grades may overlap slightly, as is pointed out later.

The 18 per cent nickel maraging steels are hardened by a simple aging treatment. Water or oil quenching normally are not required after the annealing or aging treatments since these steels are martensitic (low carbon martensite) after slow cooling from the annealing temperature, which usually is 1500 F. Aging (maraging) in the range from 850 to 950 F promotes an age-hardening reaction. The actual mechanism of this reaction has not been determined although it is being studied.

Early in the development of these alloys, it was recognized that the nickel maraging steels had certain advantages over the low-alloy quenched-and-tempered martensitic steels for many applications requiring high strength. These advantages include good forming characteristics of the annealed alloy even though it is martensitic, attainment of high strengths with a relatively simple heat treatment at moderate temperatures, minimum dimensional change and distortion on heat treatment, and virtual immunity to decarburization. Comparatively good weldability and good fracture toughness are also attributes of the maraging steels. Because of these attractive characteristics, and because of the need for improved high-strength materials for aerospace applications in general and for large solid-propellant rocket-motor cases in particular, a considerable effort has been made in the past 2 years to develop and evaluate these new steels. The objectives of this effort have been to establish optimum compositions and melting and mill practices for the various commercial forms such as sheet, plate, bar, and forgings; to determine optimum forging, machining, welding, and heat-treating procedures; and to obtain a backlog of property data that can be used in specifications and designs for these steels.

In recent studies of the metallurgical properties of maraging steel plate, it has been observed that there is a tendency for this steel to develop a banded structure. This condition causes reduced short-transverse strength and ductility. Fractures in banded plate have shown that the dark-etching portion of the banded structure has lower strength than the lighter etching portion. These studies are being continued to try to minimize the effect of banding.

In several instances, cracks have developed at welds in thick sections of maraging steels. Even though this report is not primarily concerned with the properties of welded joints, the problem is mentioned in the interest of caution. In addition, it should be noted that the maraging steels are considerably more expensive than the low-alloy martensitic steels. Consequently, use of the maraging steels is generally limited to special high-strength components for which the cost can be justified.

A preliminary review of the properties of the nickel maraging steels was presented by the Defense Metals Information Center in Memorandum 156 dated July 2, 1962. Since then, a large number of reports containing data on the maraging steels have reached DMIC. This report is a summary and review of the data presented in these other reports.

The data presented in this memorandum are limited to the 18 per cent nickel types of maraging steels (200,000 to 300,000-psi yield strengths) since most current interest in the maraging steels is in the 18 per cent nickel compositions. The composition ranges for these grades are as follows[1,2]*:

Alloying Element[a]	Grade (200)	Grade (250)	Grade (300)
Ni	17-19%	17-19%	18-19%
Co	8.0-9.0	7.0-8.5	8.5-9.5
Mo	3.0-3.5	4.6-5.2	4.6-5.2
Ti	0.15-0.25	0.3-0.5	0.5-0.8
Al	0.05-0.15	0.05-0.15	0.05-0.15

(a) Other elements (per cent): 0.03 maximum C, 0.10 maximum Mn, 0.10 maximum Si, 0.01 maximum S, and 0.01 maximum P. Other elements added (per cent): 0.003B, 0.002Zr, and 0.05Ca.

EFFECTS OF ANNEALING AND AGING CONDITIONS, HARDENER CONTENT, AND COLD WORKING ON PROPERTIES

In all of the 18 per cent nickel grades of maraging steel, transformation to martensite occurs above room temperature on cooling from the hot-working or the annealing temperatures. Typical tensile properties and hardness values for bar stock annealed 1 hour at 1500 F and air cooled are as follows[1]:

	(250) Grade, air melted	(300) Grade, vacuum melted
Yield Strength, 0.2 per cent offset, psi	95,000	110,000
Tensile Strength, psi	140,000	150,000
Elongation in 1 Inch, per cent	17	18
Reduction in Area, per cent	75	72
Hardness, Rockwell C	28-30	30-32

*References appear at the end of the report.

Since final strengthening is achieved by an aging treatment, variations in annealing and aging conditions have been studied in a number of programs in order to determine the preferred treatments for optimum properties. Variations in composition and effects of cold working on the mechanical properties also have been evaluated as discussed in the following sections.

The aging response of these alloys whether wrought or cast is affected by such factors as hardener content (titanium, molybdenum and cobalt) and by prior treatment (melting and casting procedures, hot working, warm working, cold working, and annealing processes). Effects of some of these factors are discussed. It should be emphasized that since these factors can cause variations in the properties, careful control of all of the processing procedures is required to obtain consistent properties from one heat to the next.

Annealing and Aging Conditions

As a result of the studies of annealing cycles for wrought 18 per cent nickel maraging steels, the recommended annealing treatment is usually 1 hour at 1500 F followed by air cooling. This cycle apparently results in optimum ductility since specimens annealed at lower or higher temperatures have lower values for reduction in area. This is shown in Figure 1(3). The 1-hour treatment at 1500 F is the most frequently used annealing cycle for all of the wrought grades of 18 per cent nickel maraging steel. For plate and forgings over 1 inch in thickness, the annealing treatment is often 1 hour at 1500 F per inch of thickness.

Aging of wrought products without annealing also will result in substantial strengthening. This effect is shown in Table 1 for 1/2-inch plate of 18Ni (250) maraging steel in the hot-rolled-and-aged condition and in the annealed-and-aged condition. The annealed-and-aged specimens normally have slightly higher and more uniform properties than the hot-rolled-and-aged specimens. Therefore, for best control of properties, the anneal-and-age treatment is preferred. This same effect pertains to all grades of 18 per cent nickel maraging steels(4).

The effects of variations in aging temperature and in time at temperature are also shown in Table 1. The best balance of strength and ductility is usually obtained by aging at about 900 F for 3 or 4 hours after annealing at 1500 F. Figures 2 and 3 show values for yield strength for transverse and longitudinal specimens aged at 850, 900, and 950 F for 1, 3, and 10 hours and illustrate the typical aging response for these alloys. For some heats, longitudinal specimens have higher strengths than the transverse specimens as in Table 1. For others, the transverse specimens are stronger as in Figures 2 and 3. This probably depends on the degree of cross rolling.

For cast 18 per cent nickel maraging steels, a preliminary treatment at 2100 F has been used to obtain higher properties than can be achieved with only the 1500 F annealing treatment. The improvement in properties resulting from the 2100 F treatment is shown in Table 2.

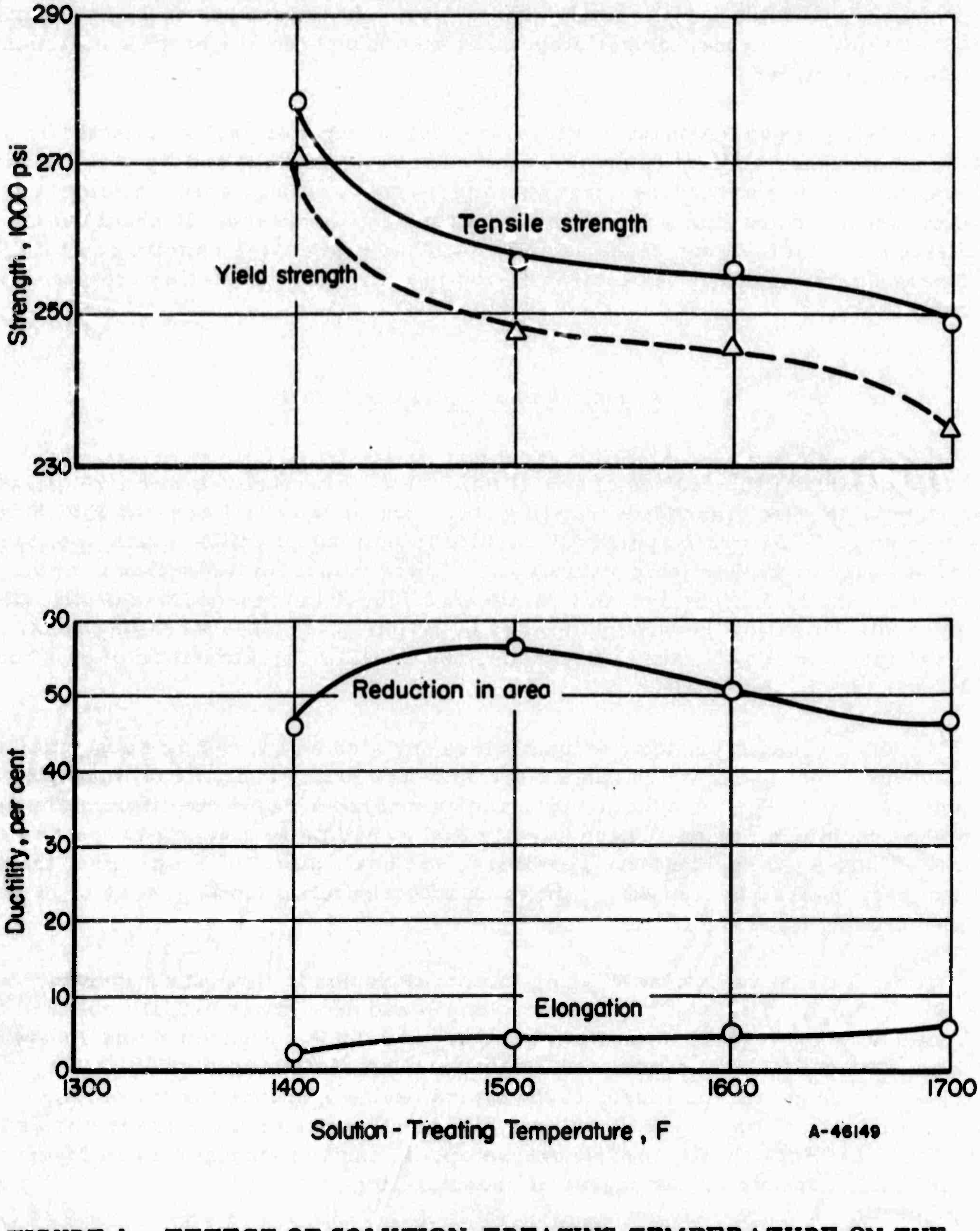


FIGURE 1. EFFECT OF SOLUTION-TREATING TEMPERATURE ON THE LONGITUDINAL PROPERTIES OF 18Ni (250) MARAGING STEEL[1]

Solution treating time — 1 hour. Aged at 900 F for 3 hours. Heat 23832; 0.01C, 0.014Mn, 0.003P, 0.002S, 0.04Si, 18.60Ni, 5.04Mo, 7.74Co, 0.08Al, 0.42Ti, 0.001Ca, 0.003Zr, 0.002B.

TABLE 1. TENSILE PROPERTIES OF AIR-MELTED 1/2-INCH PLATE OF 18Ni (250) MARAGING STEEL AS HOT ROLLED AND AGED AND AS ANNEALED AND AGED[4]

Aging Treatment Temp, F	Aging Treatment Time, hours	Direction	Yield Strength 0.2% Offset, 1000 psi	Tensile Strength, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent
			Hot Rolled and Aged			
850	4	L	252	263	9.0	39.6
850	8	L	260	272	8.6	38.9
900	4	L	265	273	7.6	37.2
900	4	T	243	255	9.5	40.7
900	8	L	283	289	7.1	38.6
900	8	T	263	272	8.0	42.9
950	2	L	264	272	7.7	38.5
950	4	L	266	276	7.6	39.2
			Annealed at 1500 F for 30 Minutes and Aged			
850	4	L	258	266	9.1	47.0
850	8	L	268	276	8.8	46.5
850	16	L	284	291	7.7	42.1
850	16	T	264	276	8.1	42.4
900	4	L	275	281	7.9	43.5
900	4	T	259	268	8.8	46.7
900	8	L	286	292	7.6	40.3
900	8	T	273	279	7.5	42.9
950	2	L	261	267	8.9	46.5
950	4	L	269	278	7.9	41.6

Note: Tests made on 1/4-inch-diameter specimens.
Composition of Heat 13371: 0.023C, 0.003P, 0.009S, 0.06Si, 18.65Ni, 8.05Co, 4.90Mo, 0.52Ti, 0.05Al.

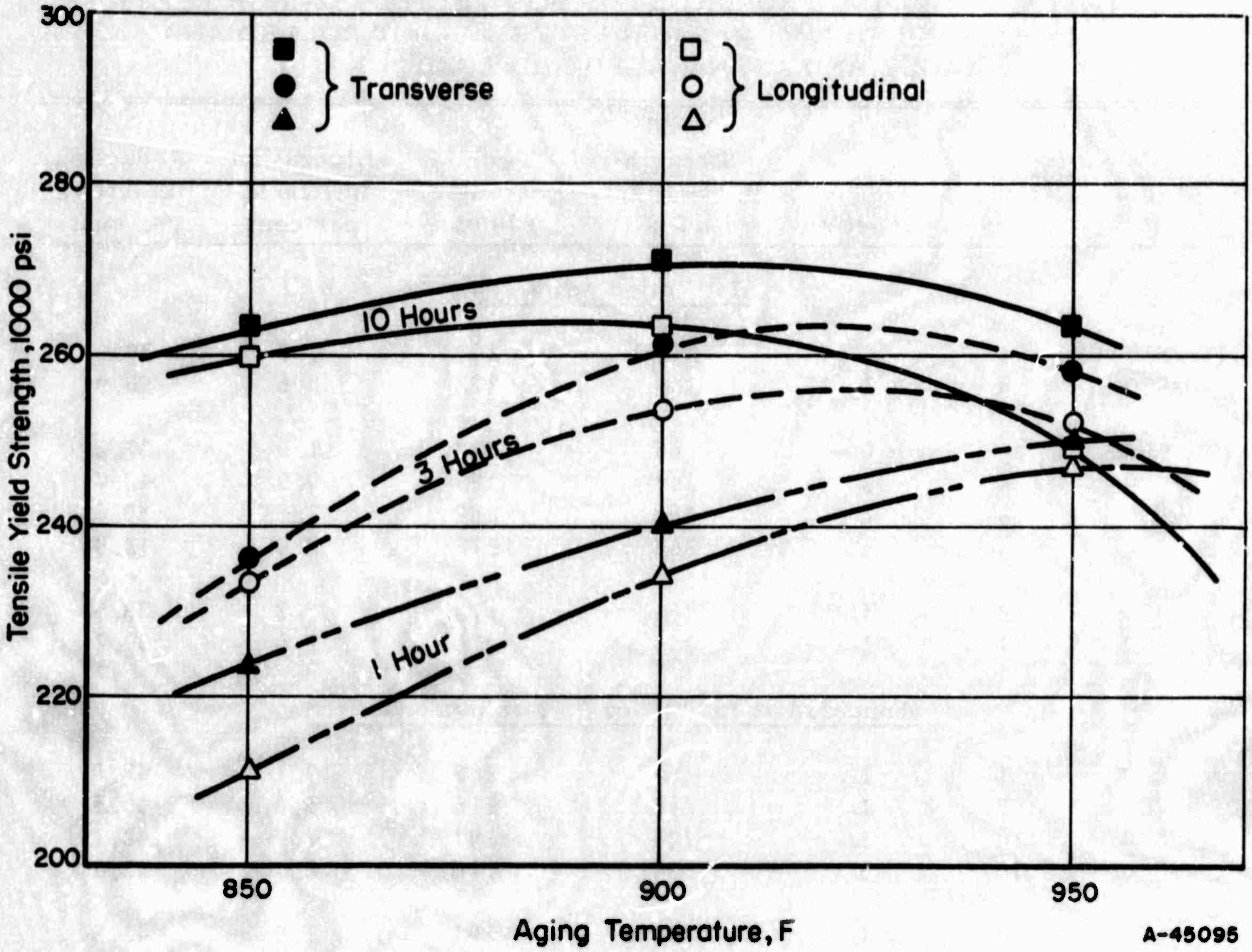


FIGURE 2. EFFECT OF AGING TREATMENT ON THE YIELD STRENGTH OF 0.115-INCH-THICK 18Ni (250) MARAGING STEEL SHEET[3,5]

Composition: 0.010C, 0.014Mn, 0.003P, 0.002S, 0.04Si, 18.60Ni, 5.04Mo, 7.74Co, 0.42Ti, 0.08Al.

Specimens annealed at 1500 F for 1 hour and air cooled before aging.

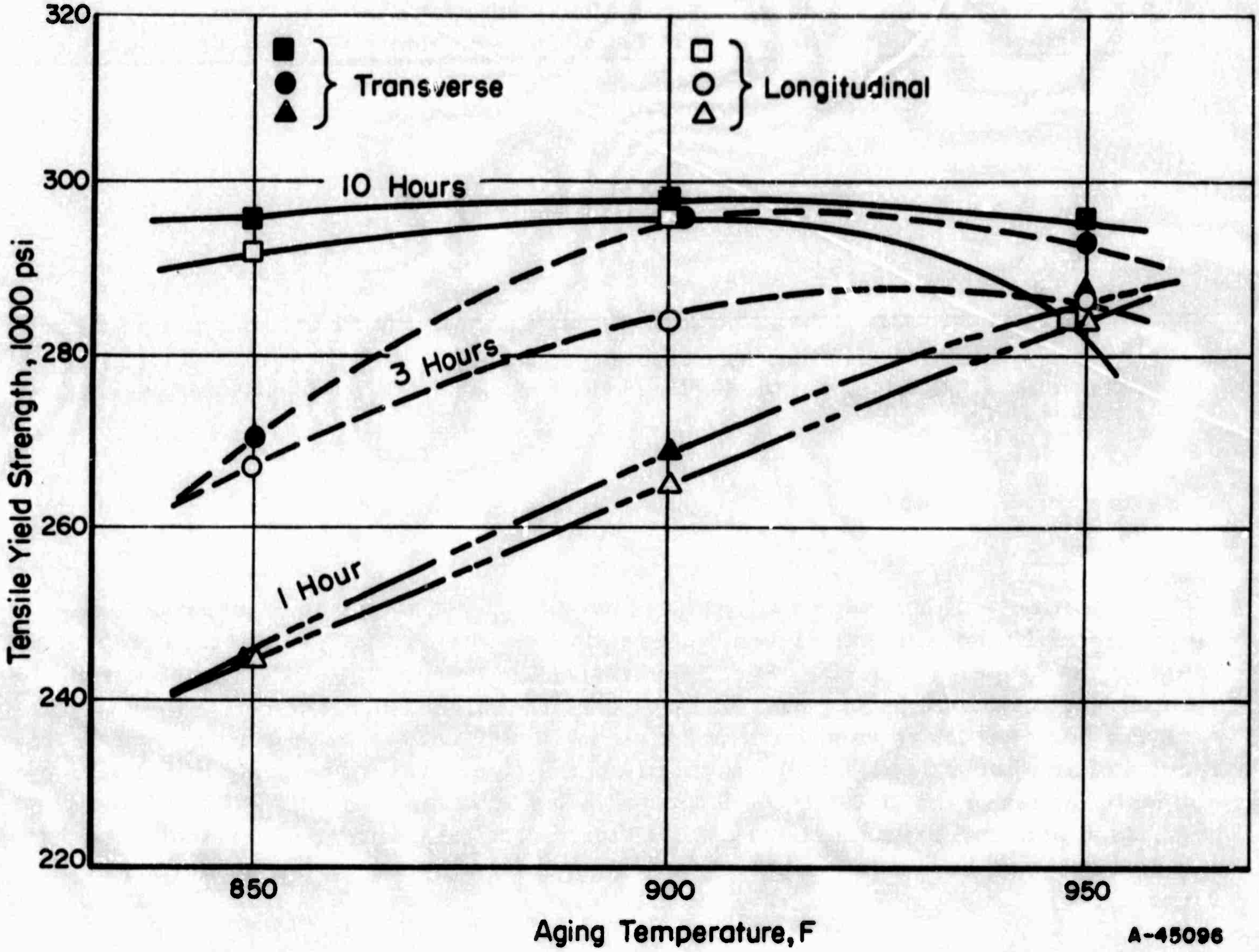


FIGURE 3. EFFECT OF AGING TREATMENT ON THE YIELD STRENGTH OF 0.115-INCH-THICK 18Ni (300) MARAGING STEEL SHEET[3,5]

Composition: 0.008C, 0.015Mn, 0.001P, 0.003S, 0.05Si, 18.61Ni, 5.00Mo, 9.05Co, 0.71Ti, 0.13Al.

Specimens annealed at 1500 F for 1 hour and air cooled before aging.

TABLE 2. EFFECT OF ANNEALING TREATMENT ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF CAST 18Ni (250) MARAGING STEEL(6)

Annealing Treatment: Temp, F	Annealing Treatment: Time, hours	Yield Strength 0.2% Offset, 1000 psi	Tensile Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent	Hardness, Rockwell C
1500	3	253	274	1.7	3.2	51
2100 1500	4 3	262	275	5.8	21.0	52
2100	4	254	270	5.7	20.2	51-52

Note: All specimens aged at 900 F for 3 hours after the annealing treatment.
Heat 06990-1: 0.03C, 0.14Si, <0.10Mn, <0.01S, <0.01P, 4.74Mo, 18.32Ni, 9.33Co, 0.45Ti, 0.12Al, 0.0035B, <0.01Zr.

Hardener Content

The effects of hardener content have been assessed by various investigators. International Nickel Company investigators have estimated that, within the composition range of the 18 per cent nickel maraging steels, the incremental effect of cobalt on the yield strength is 1000 psi for each 0.1 per cent added, for molybdenum it is 2000 psi for each 0.1 per cent added, and for titanium it is 10,000 psi for each 0.1 per cent.* The results of another investigation(7) indicate that 0.1 per cent increments of the alloying elements increase the yield strength the following amounts: cobalt, 1200 psi; molybdenum, 2800 psi; and titanium, 6000 psi. Other investigators have suggested an empirical equation relating hardener content to the strength obtained on aging, as plotted in Figure 4.

The equation

$$\text{Yield Strength (1000 psi)} = 15.1 + 9.1(\%\ \text{Co}) + 28.3(\%\ \text{Mo}) + 80.1(\%\ \text{Ti})$$

has also been proposed(4). When this equation is used to estimate the range in yield strength that is possible considering the limited ranges of hardener contents in the specification for one grade, the yield strengths may vary by as much as 35,000 psi. This indicates the need for conducting aging-response studies on each heat to be certain of the actual properties that can be achieved and to permit matching the properties of all the individual components for each fabricated item.

Although some variation is reported in the actual magnitude of the effect of each of the hardening elements, it is apparent that titanium has the greatest influence on the strength of the maraging steels, as aged. The effect of titanium content on the yield strength of the 250 and the 300 grades of 18 per cent nickel maraging steels is shown in Figures 5 and 6. The data from which these curves were plotted are presented in

*R. F. Decker, private communication.

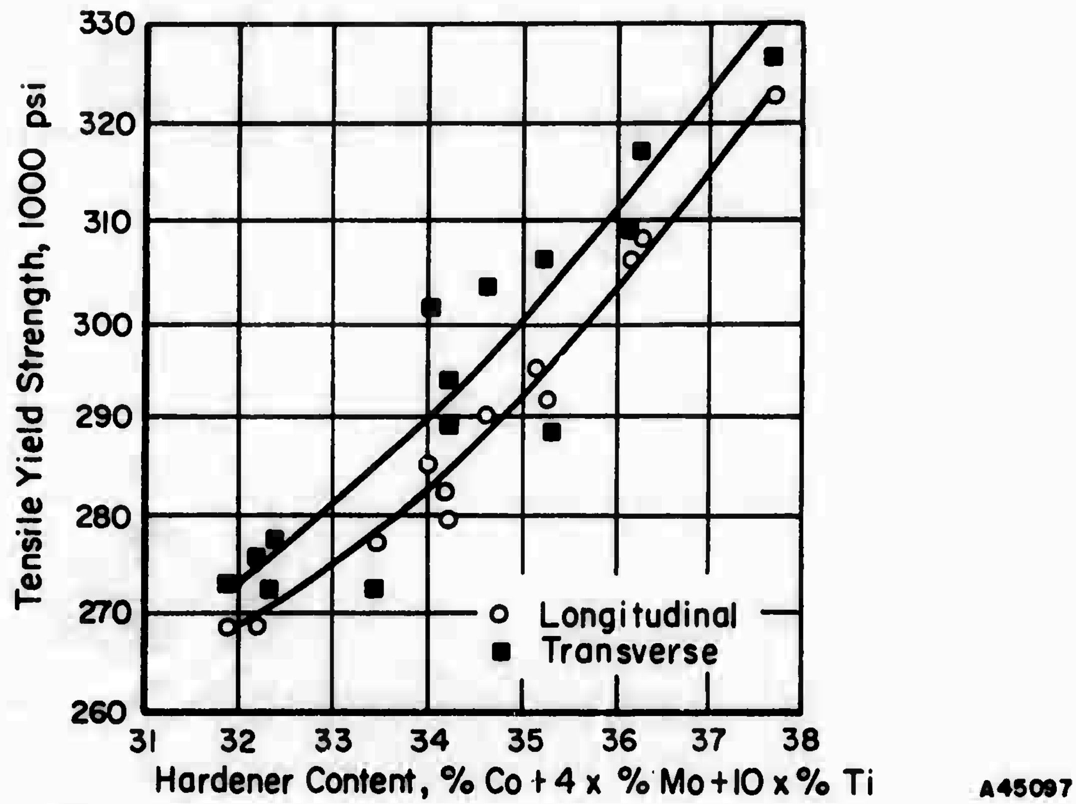


FIGURE 4. EFFECT OF ALLOY CONTENT ON THE YIELD STRENGTH OF 0.062-INCH-THICK 18Ni (300) MARAGING STEEL SHEET ANNEALED AT 1500 F FOR 1 HOUR AND AGED AT 900 F FOR 3 HOURS(8)

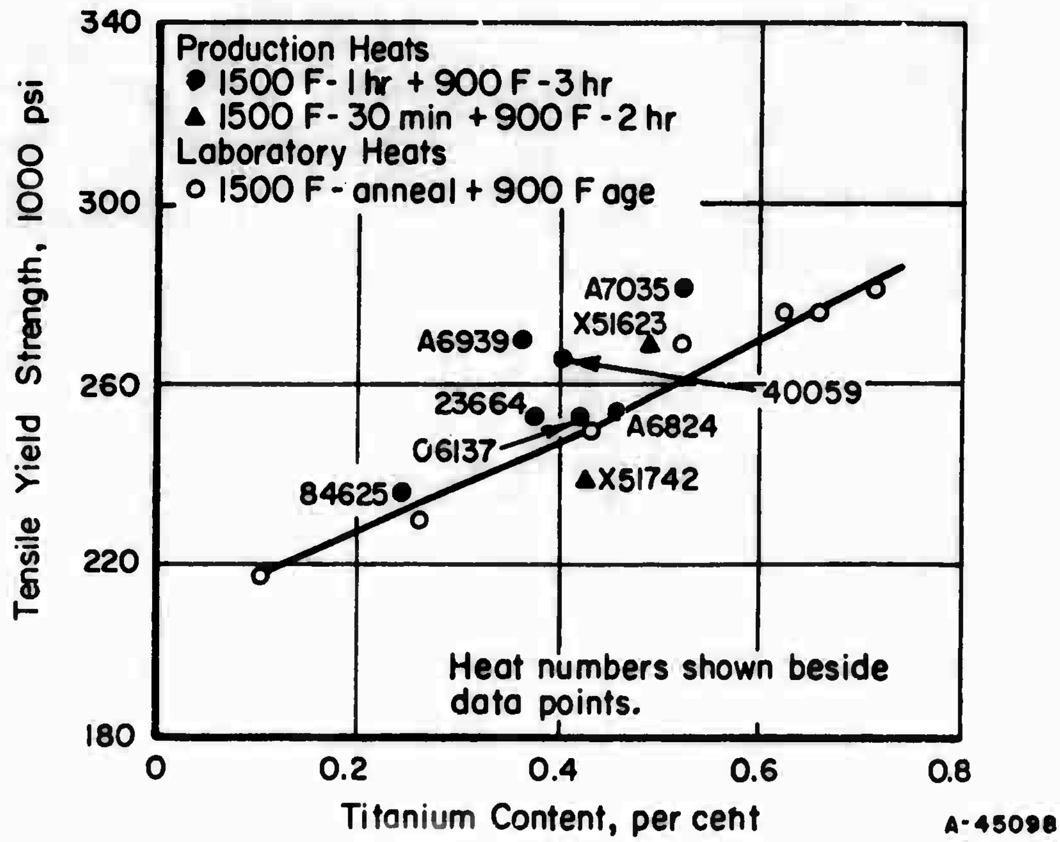


FIGURE 5. EFFECT OF TITANIUM CONTENT ON THE YIELD STRENGTH OF 18Ni (250) MARAGING STEEL

Both production size and laboratory heats are shown. (5) Compositions of heats are given in Table A-1 in the Appendix.

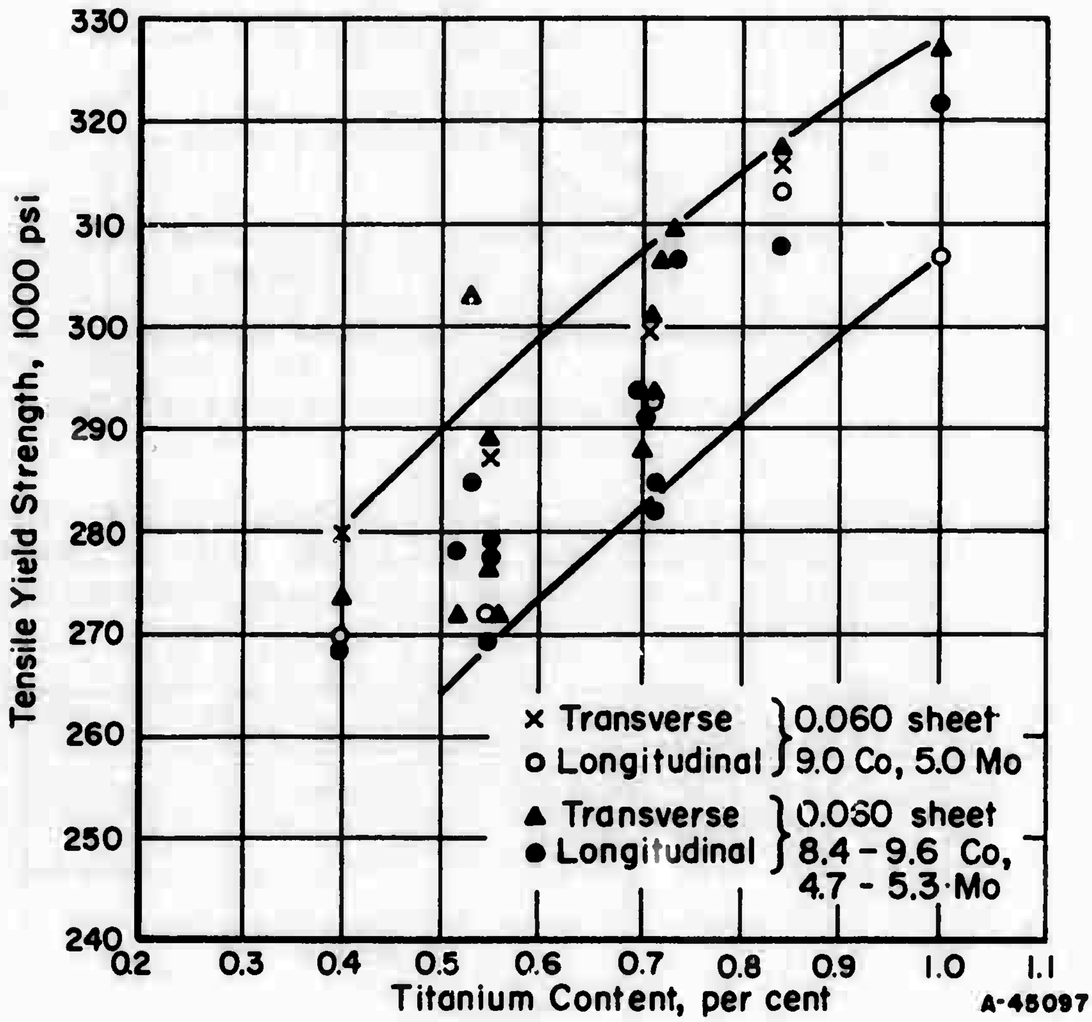


FIGURE 6. EFFECT OF TITANIUM CONTENT ON THE YIELD STRENGTH OF 18Ni (300) MARAGING STEEL ANNEALED AT 1500 F AND AGED AT 900 F FOR 3 HOURS(7,9)

See Tables A-2, A-3, and A-4 in the Appendix for compositions and properties.

Tables A-1 through A-4 in the Appendix. The data points in Figures 5 and 6 show that the titanium must be on the high side of the ranges usually specified (0.3 to 0.5 for the 250 grade and 0.5 to 0.8 for the 300 grade) if the expected yield strengths are to be attained. The variations in properties at a given titanium level are undoubtedly attributable to numerous factors including variations in the contents of the other two hardener elements, cobalt and molybdenum.

Effect of Cold Working

A number of investigations are in progress on the effects of cold working on the properties of maraging steels. Some of the data that have been accumulated are presented in Figures 7 and 8 and listed in Tables A-5 through A-8 in the Appendix. These data show that the strengths of both the 250 and the 300 grades of 18 per cent nickel maraging steel, as aged, are increased by prior cold working. Also, cold working tends to decrease slightly the time and temperature at which maximum strength is achieved during aging. These data led to the conclusion that the maximum yield strength was obtained when the metal was cold worked 50 per cent before aging, and that the optimum aging time at 900 F was 1.75 hours for the 250 grade and 5.4 hours for the 300 grade.

The effects of cold working on the tensile properties of bar stock are shown in Table 3.[10]

TABLE 3. EFFECT OF COLD WORKING ON THE TENSILE PROPERTIES OF 18Ni(250) MARAGING STEEL BAR STOCK[10]

Cold Work, per cent	0.2% Offset Yield Strength, 1000 psi	Tensile Strength, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent
0	261	264	8.6	57
25	272	277	6.5	49
50	293	298	5.2	44

Note: Aged at 900 F for 3 hours after cold working. Specimens 1/4-inch diameter.

Cold working also affects the elastic modulus of maraging steels as shown by dynamic modulus tests.[11] The variation in modulus is not only dependent on the heat-treating and cold-working cycles but also on the orientation of the specimen, as shown in Table 4 for sheet of 18Ni(250) maraging steel in several different conditions.

In highly stressed structures that require joining of various components by welding or other means, it may be advisable to match the modulus of adjoining components so the deformations under load will be as uniform as possible.

The effect of cold working on Poisson's ratio for 18Ni(250) maraging steel sheet are shown in Table 5 [tentative data by Kula[12]]. Young's modulus was 26×10^6 psi for each condition.

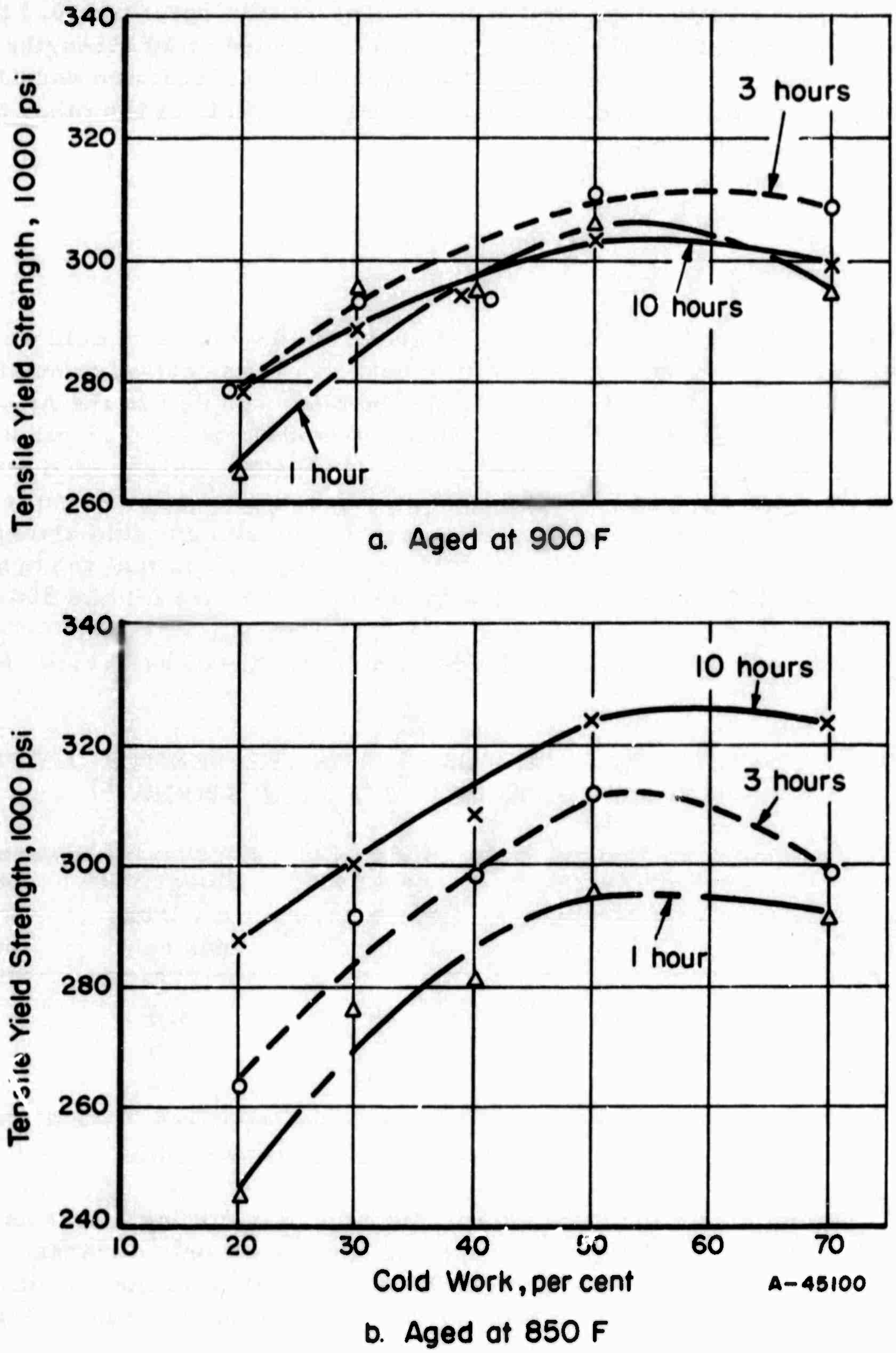
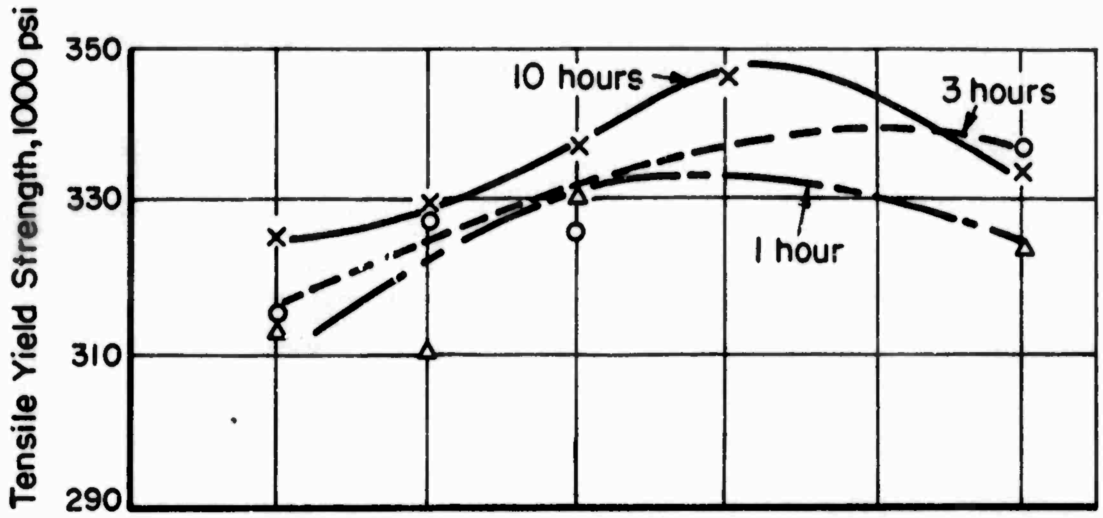
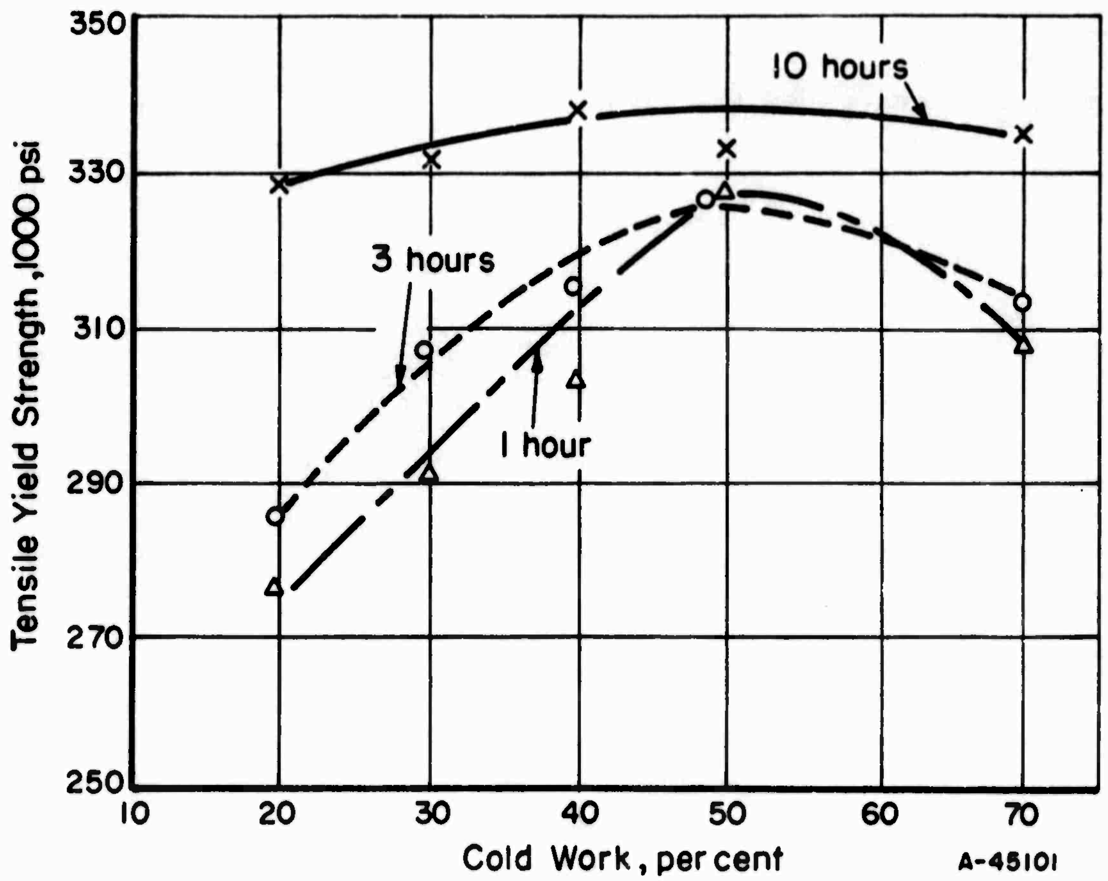


FIGURE 7. EFFECT OF COLD WORKING, AGING TIME, AND AGING TEMPERATURE ON THE LONGITUDINAL YIELD STRENGTH OF 18Ni (250) MARAGING STEEL(3)

Composition: 0.010C, 0.014Mn, 0.003P, 0.002S, 0.04Si, 18.60Ni, 5.04Mo, 7.74Co, 0.42Ti, 0.08Al.



a. Aged at 900 F



b. Aged at 850 F

FIGURE 8. EFFECT OF COLD WORKING, AGING TIME, AND AGING TEMPERATURE ON THE LONGITUDINAL YIELD STRENGTH OF 18Ni (300) MARAGING STEEL[3]

Composition: 0.008C, 0.015Mn, 0.001P, 0.003S, 0.05Si, 18.61Ni, 5.00Mo, 9.05Co, 0.71Ti, 0.13Al.

TABLE 4. EFFECT OF COLD WORKING AND ORIENTATION ON THE DYNAMIC MODULUS(11)

Condition	Dynamic Modulus, 10^6 psi	
	Longitudinal Specimens	Transverse Specimens
As received annealed at 1500 F for 15 min	25.8	27.6
Aged at 900 F for 3 hours	27.3	29.2
As-received material cold worked 60%	26.1	29.4
Cold worked 60% and aged at 900 F for 3 hours	27.8	30.9
Cold worked 60%, annealed 1500 F for 1 hour, and aged at 900 F for 3 hours	27.3	28.1
Reannealed 1500 F for 1 hour, cold worked 60%, and aged 900 F for 3 hours	27.2	30.6

Note: See Figure 10 for composition.

TABLE 5. EFFECT OF COLD WORKING ON POISSON'S RATIO

Direction	Cold Work, per cent	Poisson's Ratio
L	0	0.31
L	40	0.28
L	60	0.26
T	0	0.31
T	20	0.31
T	60	0.26

Note: Data obtained on tensile loading sheet specimens which were annealed at 1500 F, cold worked, and aged at 900 F for 3 hours. Composition: Heat C, 0.02C, 0.10Si, 0.08Mn, 0.009S, 0.009P, 18.96Ni, 7.34Co, 5.04Mo, 0.05Al, 0.29Ti, 0.004B, 0.01Zr, 0.05Ca.

The strain-hardening exponent, n, obtained on specimens from 1-inch plate having a yield strength of 230,000 psi and tensile strength of 240,000 psi was 0.039.[1]

Ausforming experiments at Lockheed[13] on specimens of 18Ni (300) maraging steel did not yield any improvement in mechanical properties. The specimens were cooled from 1500 F to 900 F or 450 F and strained about 25 per cent, cooled to room temperature, then to -100 F, and finally aged at 900 F for 3 hours.

The data presented here are only indicative of the considerable amount of data that have been accumulated on the effects of warm and cold working these steels. Much of the research being done on the effects of cold working involves the lower alloy grades of the 18 per cent nickel maraging steels.

TENSILE PROPERTIES

Data on the room-temperature tensile properties of the various grades of 18 per cent nickel maraging steels, collected from numerous sources, show the influence of form (section size), melting practice, and testing direction on the tensile properties. These data can be conveniently grouped and presented according to three mill forms:

(1) Sheet in thicknesses up to 0.25 inch

(2) Plate, in thicknesses from 0.25 to 2.5 inches

(3) Heavy sections including rounds, bars, slabs, billets, forgings, and squares.

Melting practices represented by these data include air melting, air melting with vacuum degassing, and vacuum-arc remelting.

The tensile data collected in this section represent only one condition of heat treatment: solution annealing at 1500 F followed by aging at 900 F for 3 or 4 hours. Tensile data are listed in Tables A-9 through A-17 in the Appendix. Each data point is an average of data from two or more test specimens. From these data, the minimum, maximum, and overall average tensile properties were determined and tabulated in Table A-18. The data in Table A-18 help to illustrate the scatter in tensile properties. Table A-18 also includes the number of test points used for computing the average values. This provides some indication of the significance of the overall average values reported.

The effects of section size, melting practice, and testing direction on tensile properties are shown in Figure 9, which is a bar graph of the average tensile properties (tensile strength, yield strength, and elongation) of the (200), (250), and (300) grades of the 18 per cent nickel maraging steels. It is obvious from the bar graph that the average yield strengths of all the 18Ni (200) grade forms lie well above the 200,000-psi yield-strength line and that average yield strengths of over 230,000 psi have been obtained within this grade of steel. The average yield strength levels for the 18Ni (250) grade usually lie just above the 250,000-psi yield-strength line. It appears that average yield strengths of 250,000 psi can be consistently obtained and that yield strengths up to 270,000 psi have been obtained with this grade. The data for the 18Ni (300) grade

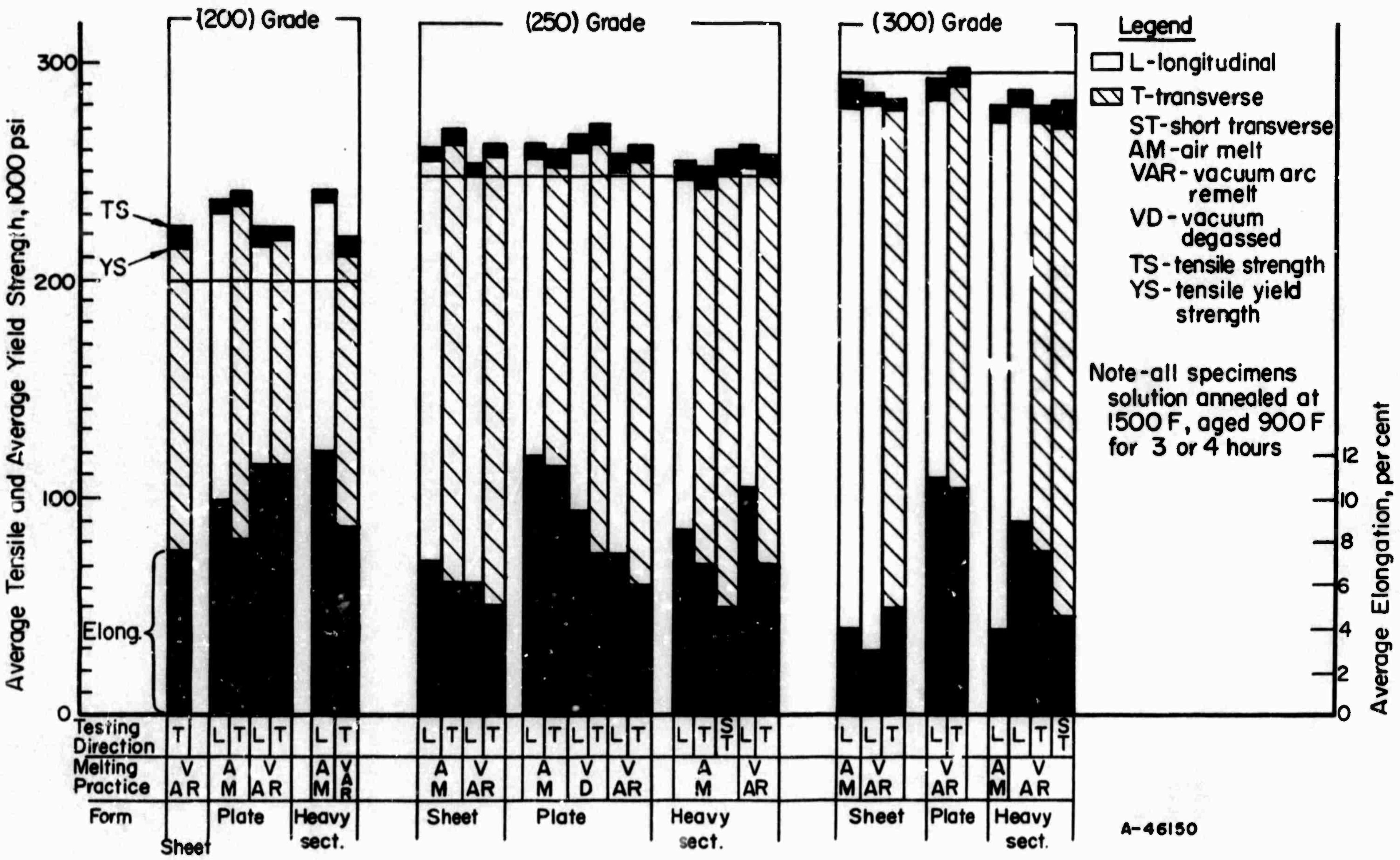


FIGURE 9. AVERAGE TENSILE PROPERTIES OF THE 18Ni MARAGING STEELS (200, 250, AND 300 GRADES) FOR VARIOUS FORMS, MELTING PRACTICES, AND TESTING DIRECTIONS

materials, in all forms, clearly indicate that average yield strengths for this grade are usually near the 280,000-psi level.

Considering the data for all the grades of maraging steels suggests several generalizations. The spread between the average tensile-strength and yield-strength values within each grade is fairly constant and overall averages about 8,000 psi. The ductility of the steels varies with the strength levels and the type of product. As the tensile strengths increase the ductility tends to decrease, while the ductility of sheet tends to be less than that of the other forms. The elongations reported are for a 1-inch gage length in most instances. For all the maraging steel grades, the average elongation ranged from 3 per cent to 12 per cent.

Effect of Section Size, Specimen Orientation, and Strain Rate

The bar graph in Figure 9 also indicates that section size generally does not influence the strength level that can be achieved for a given composition. In other words, the hardening reaction is not limited by section size for the 18 per cent nickel maraging steels as it is in the case of the quench-hardening low-alloy martensitic steels.

An example of the effect of section size on the tensile properties of a forging of 18 per cent nickel maraging steel is shown in Table 6. Specimens taken from a 4-inch-thick section had the same strengths as those from a section 0.62 inch thick. However, the ductility of the specimens taken from the transverse and short transverse directions in the thick section was lower than that for the longitudinal specimens and for the transverse specimens from the thinner web section. The ductility is dependent on the amount of hot working and on the direction of specimen orientation.

TABLE 6. AVERAGE TENSILE PROPERTIES OF 18Ni (250) MARAGING STEEL FORGING AT HEAVY AND THIN SECTIONS[14]

Location[a]	Direction	Yield Strength 0.2% Offset, 1000 psi	Tensile Strength, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent
Heavy Section	Long.	251	263	10.0	47.4
	Trans.	250	262	4.5	14.2
	ST	252	264	4.8	23.9
Web Section	Long.	254	266	10.5	53.2
	Trans.	251	263	10.0	48.1

Note: Heat W-G 10081, vacuum-arc remelted, 0.020C, 0.16Si, 0.03Mn, 0.006S, 0.005P, 18.16Ni, 4.40Mo, 7.22Co, 0.54Ti, 0.22Al.
Heat treatment, 1500 F 1 hour, air cooled, aged 900 F 3 hours.
ST = short transverse.

(a) Heavy section was 4 inches thick; web section was 0.62 inch thick.

Tensile data on specimens from a 40-inch-diameter front dome forging for the Pershing missile motor case further illustrate the effect of specimen orientation[14]:

	Radial and Tangential Directions	Short Transverse Direction (Average)
Yield Strength, psi	278,000-286,000	279,100
Tensile Strength, psi	289,600-297,000	288,600
Elongation in 1 Inch, per cent	6.5-10.0	4.3
Reduction in Area, per cent	34.1-48.2	16.5

These specimens were annealed 1 hour at 1500 F, air cooled and aged at 900 F for 3 hours. The tensile and yield strengths fall within relatively narrow bands but the ductility is substantially lower for specimens taken from the short transverse direction than from the other directions. These data also indicate that the ductility is influenced by the degree of hot working.

Typical tensile properties from the longitudinal and transverse directions for sheet and plate of 18 per cent nickel maraging steel are shown in Table 7. It is assumed that the longitudinal direction is the same as the direction of the final rolling passes. Obviously, there is little if any difference in the longitudinal and transverse directions in the sheet and plate from these heats. Apparently the degree of cross rolling was adequate to overcome any differences that might be detected by unnotched tensile tests.

TABLE 7. EFFECT OF ORIENTATION ON THE TENSILE PROPERTIES OF 18 PER CENT NICKEL MARAGING STEEL SHEET AND PLATE

Thickness, inch	Direction	Yield Strength 0.2% Offset, 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Heat	Reference
0.075	Long.	230	237	7.8	24285	15
	Trans.	233	242	7.5	(VAR)[a]	
0.075	Long.	266	274	7.2	W-24178	
	Trans.	271	278	6.8	(VAR)[a]	
0.065	Long.	251	264	7.0	06498	
	Trans.	257	268	6.8	(VAR)[a]	
0.50	Long.	248	255	13	X-13371	16
	Trans.	244	250	12	(Air melt)	

Note: Aging treatment: 900 F 3 hours.
(a) Vacuum-arc remelt.

In evaluating the tensile properties of sheet and plate using full-thickness specimens, the thickness of the material has a marked effect on the elongation as shown in Table 8. These data show a definite trend in thickness versus elongation from 0.025 to 0.250-inch thickness for the (250) and (300) grades. This effect should be considered when setting up specifications for these alloys. The data in Table 8 also show the effect of gage length in measuring the elongation. The elongation in a 1-inch gage length is

TABLE 8. TENSILE PROPERTIES OF TRANSVERSE SPECIMENS OF 18 PER CENT NICKEL MARAGING STEEL SHEET AND PLATE OF VARIOUS THICKNESSES[17]

Thickness, inch	Yield Strength 0.2% Offset, 1000 psi	Tensile Strength, 1000 psi	Elongation In 1 Inch, per cent	Elongation In 2 Inches, per cent
		(250) Grade		
0.025	274	280	2.0	1.0
0.040	268	269	3.0	1.5
0.050	274	276	4.5	2.0
0.062	262	268	5.0	2.5
0.075	284	289	6.0	3.0
0.090	261	264	6.0	3.0
0.125	264	279	7.0	3.5
0.187	252	264	6.0	3.0
0.250	274	278	9.0	4.5
0.375	272	275	12.0	6.0
0.500	266	268	10.0	5.0
0.750	263	266	10.0	5.0
		(300) Grade		
0.025	294	300	2.0	1.0
0.040	293	302	3.5	2.0
0.050	299	300	4.5	2.5
0.062	303	318	5.0	2.5
0.075	305	306	6.0	3.0
0.087	309	310	6.0	3.0
0.098	308	309	6.5	3.5
0.125	291	299	6.5	3.5
0.190	276	290	7.5	4.0
0.250	295	304	10.0	5.0
0.500	276	284	9.0	4.5

Note: All specimens were vacuum-arc remelted material solution annealed for 1 hour per inch of thickness and air cooled. Each specimen was aged for 3 hours at 900 F. Data are averages for two specimens.

twice that in a 2-inch gage length (when measured on the same specimen). This is characteristic of materials that develop little or no uniform elongation before necking occurs during tensile testing. It is also characteristic of materials that have yield strengths only slightly lower than the ultimate strengths.

Only limited data are available on the effect of strain rate on the tensile properties of the 18 per cent nickel maraging steels. However, results of tests at 0.005, 0.05, and 0.102 inch per inch per minute on one series of specimens from bar stock of (300) grade indicated that there was a slight increase in tensile and yield strengths for both longitudinal and transverse specimens within this range of strain rates.[18] Data obtained by other investigators[13] on three sets of specimens of 18Ni (300) sheet aged at 900 F for 3 hours and tested at 0.005 inch per inch per minute and at crosshead speeds of 1 inch and 2 inches per minute also indicate that this alloy is not strain-rate sensitive within this range.

Effect of Melting Practice and Grain Size

From the bar graph in Figure 9, there does not appear to be a consistent difference in tensile properties attributable to melting practice. This is further illustrated by the tensile data presented in Table 9 for 0.5-inch-thick plate from five heats of 18 per cent nickel maraging steel made by air melting, by air melting plus vacuum degassing, and by vacuum arc remelting. The differences in properties can be more easily attributed to variations in composition rather than melting practice.

TABLE 9. TENSILE PROPERTIES OF 0.5-INCH-THICK PLATE OF 18 PER CENT NICKEL MARAGING STEEL PRODUCED BY DIFFERENT MELTING PRACTICES[4]

Heat	Melting Practice	Direction	Yield Strength 0.2% Offset, 1000 psi	Tensile Strength, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent
13371	Air melted	Long.	274.7	280.8	7.9	43.5
		Trans.	259.3	267.7	8.8	46.7
120D163	Air melted + vacuum degassed	Long.	257.8	269.6	9.5	45.9
		Trans.	271.0	279.7	8.8	41.4
3888472	Vacuum-arc remelted	Long.	277.5	287.7	9.7	42.0
		Trans.	273.7	283.0	9.0	40.5
3888473	Vacuum-arc remelted	Long.	277.4	286.5	8.2	38.6
		Trans.	282.1	293.4	8.8	39.3
07148	Vacuum-arc remelted	Long.	291.7	300.8	7.5	39.6
		Trans.	291.5	301.0	7.2	36.7

Note: Heat treatment: 1500 F 30 minutes, air cooled, 900 F 4 hours.

Compositions:

Heat	C	Mn	P	S	Si	Ni	Co	Mo	Ti	Al
13371	0.023	--	0.003	0.009	0.06	18.65	8.05	4.90	0.52	0.05
120D163	0.016	--	0.005	0.003	0.18	18.60	8.00	4.95	0.48	0.06
3888472	0.019	0.025	0.006	0.003	0.08	18.60	9.10	5.10	0.62	0.07
3888473	0.020	0.03	0.005	0.003	0.07	18.80	8.82	4.85	0.65	0.07
07148	0.018	0.03	0.006	0.003	0.09	18.70	9.30	5.12	0.65	0.39

The effect of melting practice is examined also in later sections from the viewpoint of notched properties and fatigue properties.

While investigating the cause for low ductility in a 4 by 4-3/4-inch 18Ni (300) billet, it was found that the grain size of the billet ranged from Grain Size No. 2 near the surface to No. 5-6 at the center[18]. Results of tensile tests on specimens taken from various locations in the billet indicated that the grain size had a marked effect on the ductility. The data were as follows:

Grain Size No.	2	2-3	3-4	4-5	5-7
Elongation, per cent	0	4.4	6.3	6.9	6.3
Reduction in Area, per cent	19.6	29.9	31.5	35.8	40.3

The tensile strength was 288,000 to 294,000 psi and the yield strength was 276,000 to 284,000 psi for the specimens from all the locations. It appears therefore that variations in the grain size have little if any effect on the unnotched tensile strength and yield strength but that these variations do have a marked effect on the ductility. Since the grain size is largely dependent on the degree of hot working and the finishing temperature, one objective in forging and hot rolling operations is to finish at as low a temperature as practical in the hot-working range consistent with the required reductions.

COMPRESSIVE, SHEAR, BEARING, AND DYNAMIC MODULUS PROPERTIES

As shown in Tables 10 and 11, only a few data for compressive, shear, and bearing strength properties for the maraging steels are available and these correspond to specific tensile-strength levels. In order to estimate the strength parameters at other tensile-strength levels, the data have been nondimensionalized by dividing each strength value by the corresponding tensile ultimate or yield strength. Corresponding values for AISI 4340 steel heat treated to a minimum tensile strength of 260,000 psi are included in these tables for comparison. A reasonably close relationship between the corresponding ratios for these two types of steel appears to exist.

Dynamic modulus data have been obtained on one heat of 18Ni (250) maraging steel sheet 1/8 inch thick in various orientations.[11] The sheet was mill annealed at 1500 F for 1 hour and cooled in air. Data for specimens that were reannealed at 1500 F for 15 minutes, then aged at 900 F for 0.5, 1.5, and 3 hours, are shown graphically in Figure 10. The various aging times and specimen orientations (as well as aging temperatures and amounts of cold working which were discussed previously) have marked effects on the modulus values. These variations in modulus may represent a problem to designers in planning large welded structures in which uniform elastic deformation is desired. Nonuniform elastic deformation in two pieces joined by a weld will cause increased stresses at the weld.

TABLE 10. ROOM-TEMPERATURE STRENGTH RATIOS FOR COMPRESSIVE AND SHEAR STRENGTHS OF 18 PER CENT NICKEL MARAGING STEELS AGED AT 900 F FOR 3 HOURS AND FOR AISI 4340 STEEL AT 260,000-PSI TENSILE STRENGTH

Form	Grade	Direction	Compressive Yield Strength, psi / Tensile Yield Strength, psi	Shear Strength, psi / Tensile Strength, psi	Heat	Reference
Sheet	(250)	L	$\frac{247,000}{252,000} = 0.98$	$\frac{143,000}{262,000} = 0.55$	--	2
Sheet	(250)[(a)]	T	$\frac{296,000}{289,000} = 1.02$	--	23832	19
Plate	(250)	L	$\frac{247,000}{230,000} = 1.07$	$\frac{143,000}{240,000} = 0.60$	--	1, 20
		T	$\frac{248,000}{228,000} = 1.09$	$\frac{143,000}{236,000} = 0.61$	--	
Bar, 1/4" D	(250)	L	--	$\frac{149,000}{264,000} = 0.56$	--	10
Bar, 1/4" D	(300)	L	--	$\frac{167,000}{302,000} = 0.55$	--	10
Bar	(300)	L	$\frac{287,000}{272,000} = 1.06$	$\frac{163,000}{281,000} = 0.58$	06989	21
Bar	(300)	L	$\frac{289,000}{272,000} = 1.06$	$\frac{162,000}{282,000} = 0.58$	07081	18, 21
AISI 4340	--	--	1.12[(b)]	0.57[(b)]	--	

(a) This heat has been designated as (250) grade but its properties are more like the (300) grade.
(b) Ratios for AISI 4340 steel, heat treated to 260,000-psi minimum tensile strength, MIL-HDBK-5, "Strength of Metal Aircraft Elements", March, 1961.

TABLE 11. ROOM-TEMPERATURE STRENGTH RATIOS FOR BEARING STRENGTHS OF 18Ni (300) MARAGING STEEL BAR AGED AT 900 F FOR 3 HOURS AND FOR AISI 4340 STEEL AT 260,000-PSI TENSILE STRENGTH

	Heat: 06989	07081	AISI 4340 Steel
Bearing Strength (e/D = 1.5), psi / Tensile Strength, psi	$\frac{391,000}{281,000} = 1.39$	$\frac{402,000}{282,000} = 1.43$	1.33
Bearing Strength (e/D = 2), psi / Tensile Strength, psi	$\frac{500,000}{281,000} = 1.78$	$\frac{513,000}{282,000} = 1.82$	1.69
Bearing Yield Strength (e/D = 1.5), psi / Tensile Yield Strength, psi	$\frac{382,000}{272,000} = 1.40$	$\frac{372,000}{272,000} = 1.37$	1.44
Bearing Yield Strength (e/D = 2), psi / Tensile Yield Strength, psi	$\frac{474,000}{272,000} = 1.75$	$\frac{431,000}{272,000} = 1.58$	1.59
References	21	21	MIL-HDBK-5

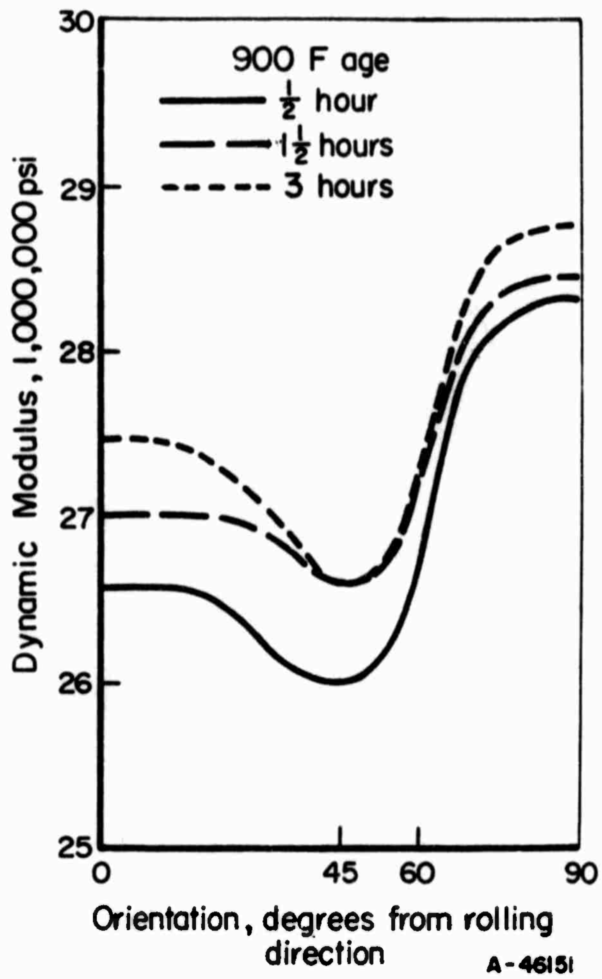


FIGURE 10. EFFECT OF SPECIMEN ORIENTATION AND AGING TIME ON DYNAMIC MODULUS OF 18Ni (250) MARAGING STEEL SHEET

Specimens reannealed at 1500 F for 15 minutes, then aged at 900 F for 1/2, 1-1/2, and 3 hours. Tensile properties in transverse direction: 250,000 to 264,000 psi yield strength, 278,000 psi tensile strength, and 4.5 to 5.5 per cent elongation in 1 inch. Composition: 0.02C, 0.21Si, 0.01Mn, 0.007S, 0.006P, 18.45Ni, 4.65Mo, 7.55Co, 0.51Ti, 0.07Al.

EFFECT OF TEMPERATURE ON THE SHORT-TIME MECHANICAL PROPERTIES

Studies of the mechanical properties of the 18 per cent nickel maraging steels at cryogenic and elevated temperatures have indicated that their usefulness is not limited to ambient-temperature applications. Typical tensile properties at cryogenic temperatures for the 18Ni (250) alloy are shown in Figure 11.[12] As for most other engineering alloys, the strength increases as the testing temperature is decreased below room temperature. The ductility and impact properties tend to decrease as the temperature is decreased. The maraging steels do not have the corrosion resistance (as do stainless steels, aluminum, and titanium alloys) that is usually desired for cryogenic applications, but they might be considered for certain applications to -320 F.

The elevated-temperature properties of the maraging steels have been determined by a number of investigators and those at the INCO Laboratories have developed a modified composition with improved properties to 1000 F. The modification in composition, as well as use of an 1800 F annealing temperature, are intended to raise the austenite reversion temperature – that is, to increase the stability of the martensite. Elevated-temperature tensile properties of the improved alloy containing 15.2 per cent nickel and an alloy within the 18Ni (300) type composition are shown in Table 12. It will be seen that these alloys have interesting properties for service in the range from room temperature to 1000 F. At 1000 F, only a small amount of surface scale forms on these alloys in an air atmosphere[22].

TABLE 12. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF MARAGING STEEL AS 3/4-INCH-DIAMETER BAR STOCK

Heat	Heat Treatment	Test Temp, F	Yield Strength, 1000 psi	Tensile Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent	Reference
32[a]	1800 F, air cool, 900 F, 3 hr	70	281	300	6	23	22
		300	251	272	8	32	
		500	235	259	9	40	
		800	218	241	10	41	
		900	205	231	12	49	
		1000	186	203	16	60	
06461[b]	1500 F, air cool, 900 F, 3 hr	RT	286	293	11	52	23
		600	230	245	11	51	
		900	200	217	16	59	

(a) Heat 32 (induction melted): 15.2Ni, 9.2Co, 5.1Mo, 0.70Ti (composition for use at elevated temperatures).
(b) Heat 06461 (vacuum-arc remelted) 18.77Ni, 8.98Co, 4.88Mo, 0.77Ti.

Additional data on the effect of temperature on the short-time mechanical properties of the wrought 18 per cent nickel maraging steels are recorded in Tables A-19 to A-23 in the Appendix. Since the variation which prevails in room-temperature tensile properties has been covered earlier in this report, room-temperature properties are duplicated in these tables only to the extent that they serve as a reference base for properties at elevated and cryogenic temperatures and for miscellaneous mechanical properties at room temperature. In most cases, the values listed are averages of several test points. An attempt has been made to include all of the pertinent information that was available in preparing these tables.

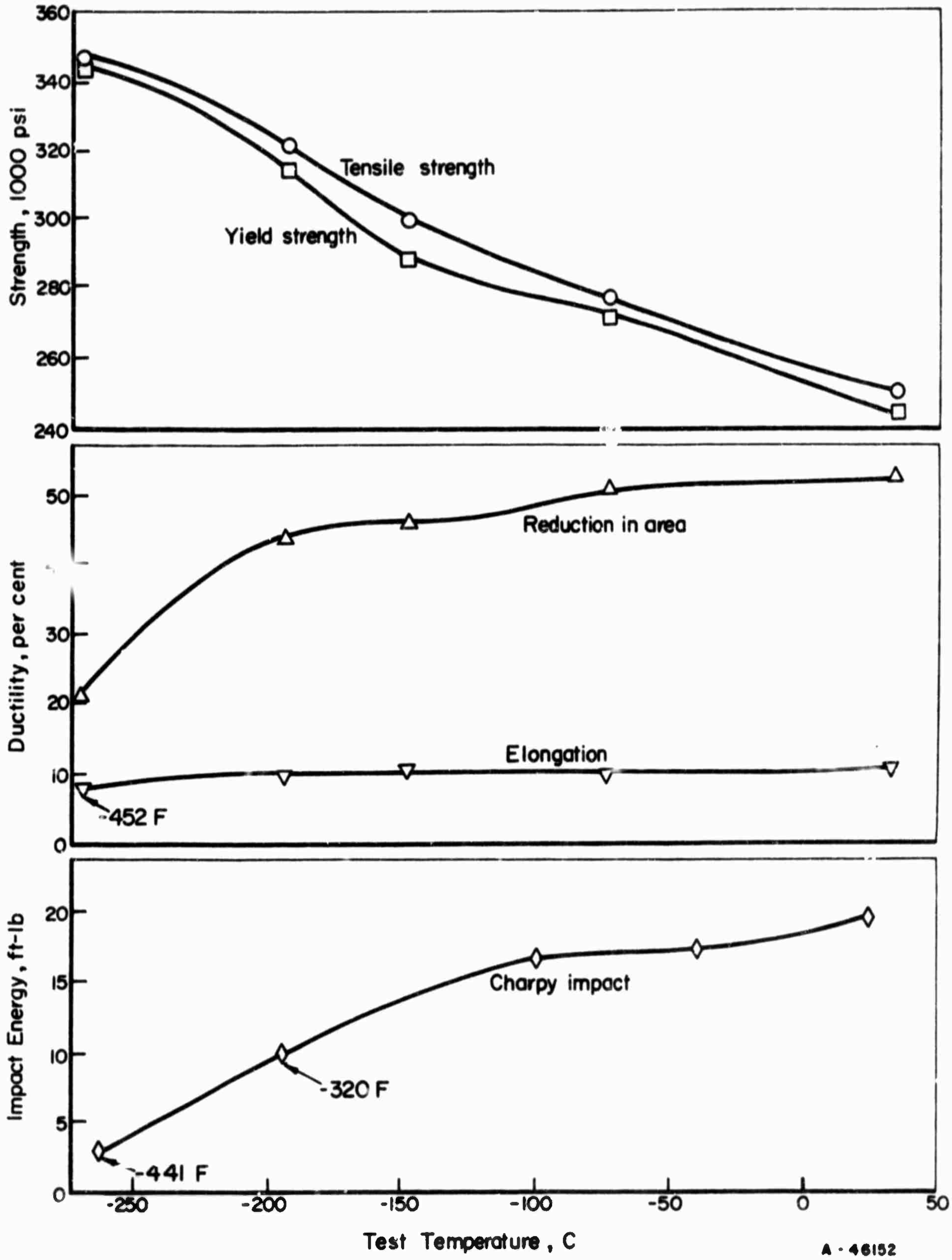


FIGURE 11. TENSILE AND IMPACT PROPERTIES OF 18Ni (250) MARAGING STEEL PLATE AT CRYOGENIC TEMPERATURES [1/2-INCH PLATE, HEAT A, KULA[12]]

Composition: 0.02C, 0.09Si, 0.07Mn, 0.009S, 0.004P, 18.39Ni, 7.83Co, 4.82Mo, 0.07Al, 0.35Ti.

In preparing design data for inclusion in MIL-HDBK-5, "Strength of Metal Aircraft Elements", and similar documents, it has been found that short-time elevated-temperature strength data are most easily handled on a nondimensional basis. That is, each data point is represented as a percentage of the corresponding room-temperature value. In this manner, elevated-temperature data that exhibit some degree of scatter on a dimensional basis can often be reduced to a smooth curve for which scatter is within the range of that normally attributed to variations in testing techniques.

Proceeding in this manner, ultimate-tensile-strength and tensile-yield-strength values from Tables A-19 and A-20 in the Appendix were nondimensionalized and are plotted in Figures 12 and 13. In preparing these figures, it was found that the mean curves drawn through all data points fit equally well for the steels of the 18Ni (250) and 18Ni (300) grades. To use these figures to estimate the strength of a specific lot of 18 per cent nickel maraging steel at some specified temperature, it is only necessary to read the percentage value from the mean curve at that temperature and multiply the room-temperature strength of the material by that percentage.

Elevated-temperature tensile properties for one heat of cast 18Ni (250) maraging steel are presented in Table A-21 in the Appendix. The strengths of the cast alloy at the elevated temperatures are comparable with those of the wrought product but the ductility tends to be a little lower.

Bearing-ultimate- and bearing-yield-strength data points from Table A-23 were considered too few to justify drawing an effect-of-temperature curve through them. However, they were both found to fit the tensile-ultimate strength curve in Figure 12 reasonably well; thus, this one curve can be considered applicable to all three of these strength parameters. Likewise, compressive-yield- and shear-ultimate-strength data from Table A-23 were found to fit the tensile yield strength curve, Figure 13.

Modulus of elasticity in tension is considered to be independent of strength level. Consequently, these values are plotted on a dimensional basis in Figure 14 (from Table A-22). It should be pointed out that these are engineering values of the tensile modulus; that is, they represent slopes of the elastic portions of tensile stress-strain diagrams. For this reason, these values may lie slightly below those determined by resonant-frequency techniques, particularly at elevated temperatures.

Average stress-strain curves for room temperature and low and elevated temperatures, tangent and secant modulus curves, and true stress-true strain curves for 18Ni (250) and 18Ni (300) maraging steels are presented in Figures A-1 to A-8 in the Appendix.

Ductility data were not found amenable to graphic presentation. In general, ductility was found to be nearly constant between room temperature and 800 F, increasing with temperature above 800 F and decreasing with temperature below room temperature.

Data on the effect of elevated-temperature exposure on the room-temperature tensile properties are available for four heats of the 18 per cent nickel maraging steels. These data are collected in Table A-24 in the Appendix. Apparently there is no effect of exposure at 500 F for 1000 hours. In some instances, there may be some effect of exposure at 600 F for extended times, but this effect becomes more obvious at 650 F. Exposure at 650 F for 1000 hours causes slightly increased strengths with substantial reductions in ductility. This trend is continued for somewhat higher exposure temperatures. It is likely that the more stable 15.2 per cent nickel alloy would show less effect from the elevated-temperature exposure than the alloys in Table A-24.

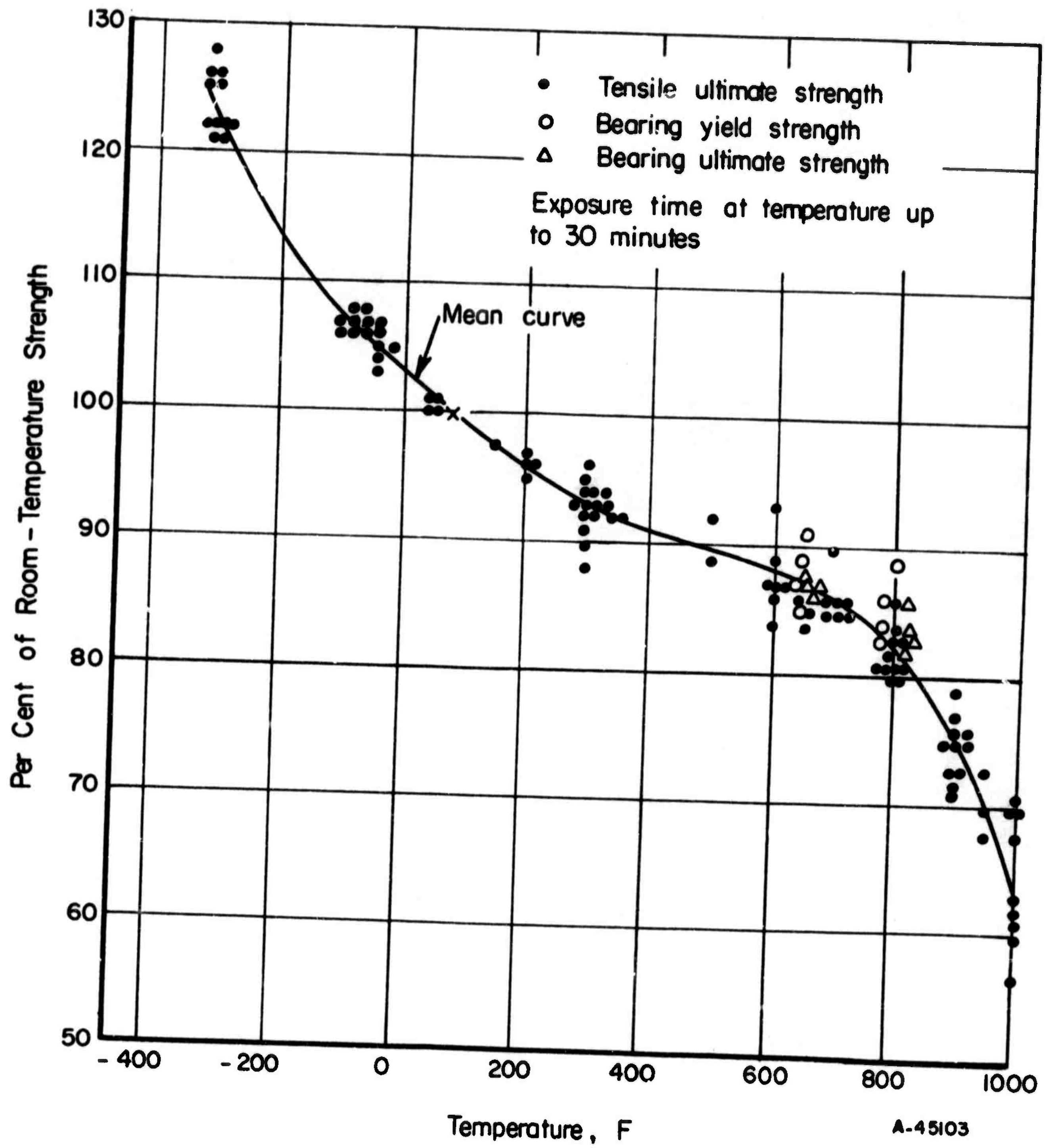


FIGURE 12. EFFECT OF TEMPERATURE ON THE ULTIMATE TENSILE STRENGTH OF 18 PER CENT NICKEL MARAGING STEELS AGED AT 900 F FOR 3 HOURS (FROM TABLES A-19, A-20, AND A-23)

Points for bearing yield and bearing ultimate strength also are included.

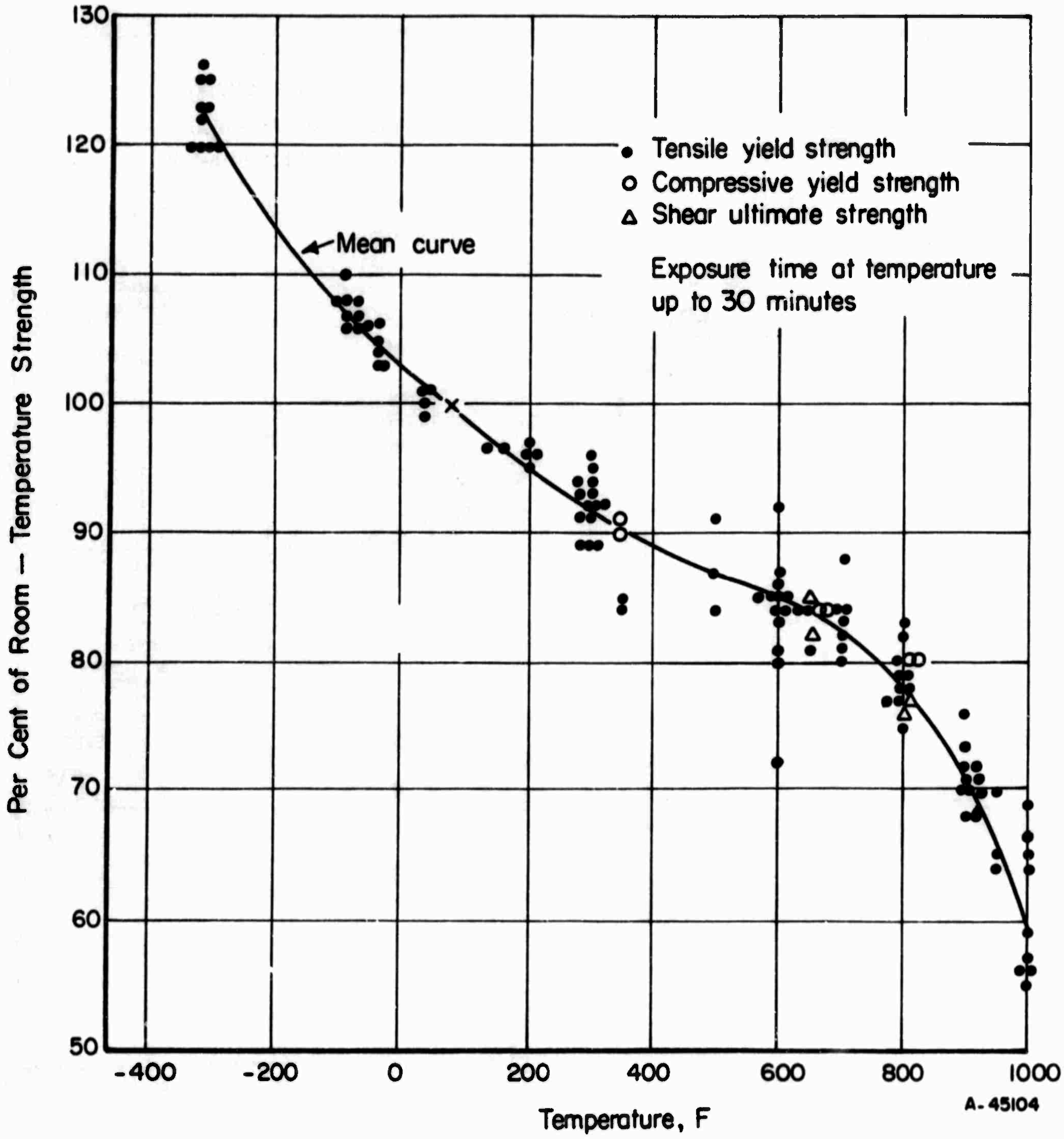


FIGURE 13. EFFECT OF TEMPERATURE ON THE TENSILE YIELD STRENGTH AND COMPRESSIVE YIELD STRENGTH OF 18 PER CENT NICKEL MARAGING STEELS AGED AT 900 F FOR 3 HOURS (FROM TABLES A-19, A-20, AND A-23)

Points for shear ultimate strength also are included.

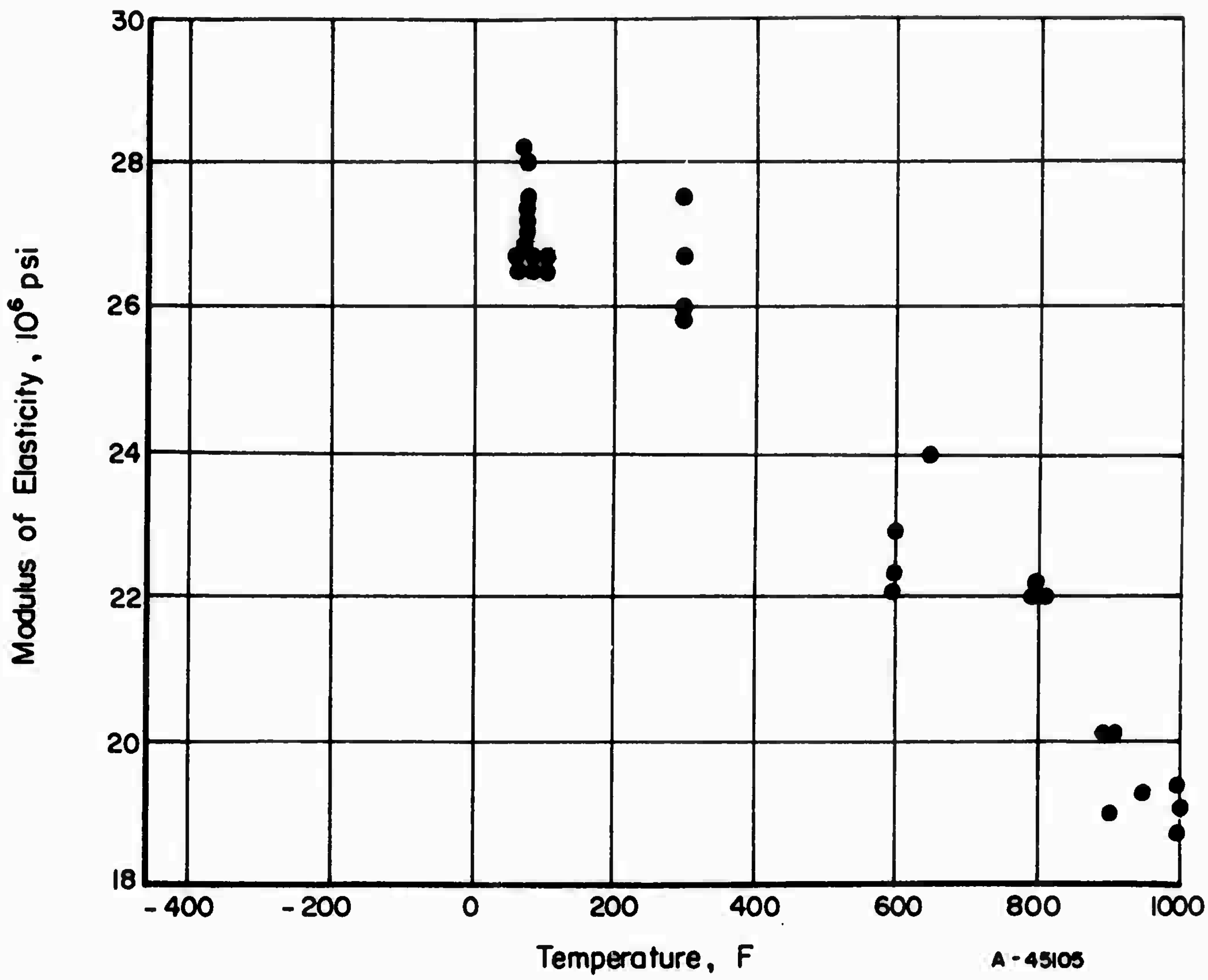


FIGURE 14. EFFECT OF TEMPERATURE ON THE ENGINEERING MODULUS OF ELASTICITY IN TENSION OF 18 PER CENT NICKEL MARAGING STEELS AGED AT 900 F FOR 3 HOURS (FROM TABLE A-22)

PROPERTIES OF NOTCHED SPECIMENS

Charpy Impact Properties

Charpy V-notch impact data for the 18 per cent nickel maraging steels in the form of plate, bar, forgings, billets, and castings are presented in Tables A-25, A-26, and A-27 in the Appendix. Representative Charpy data over a range of temperatures for maraged plate and bar are shown in Figures 11, 15, 16, and 17. From Figure 15, it is apparent that as-aged plate material does not have a well-defined Charpy transition temperature. With but two exceptions, the maximum impact energy from room-temperature tests on longitudinal specimens from plate was 26 foot-pounds (Table A-25). This is nearly at the level of the upper plateau of Charpy values for plate for tests at higher temperatures (to 1000 F). At cryogenic temperatures, the impact energy decreases steadily as the temperature is decreased. The data in Figure 15 also illustrate the marked difference in impact energies that have been obtained for longitudinal and transverse specimens from the same plate.

There is more scatter among the Charpy impact data for bar, forgings, and billets. This is probably the result of a greater range of processing variables than for plate. From the data for bar material, shown in Figure 16, it appears that the upper plateau in the Charpy values may not be reached for certain heats until testing temperatures of 300 F and higher are used. Consequently, for some of the bar materials, room-temperature Charpy tests may be in the transition range. The data in Figure 16 also illustrate the problem of low impact properties in forgings, a matter which is being studied in several laboratories.

The effect of austenite reversion on the Charpy impact properties at temperatures over 1000 F is shown in Figure 17. Increased austenite content results in increased impact energy above 1000 F.

An illustration of the effect of direction of grain on the impact properties of a 4 by 4-inch billet is presented in Figure 18. Obviously, the effect of specimen orientation on Charpy impact properties is very pronounced in large wrought sections.

Charpy impact data have been obtained on specimens from castings of maraging steels by investigators at several laboratories, in the course of developing alloys for castings. As shown in Table A-27 in the Appendix, room-temperature impact energy obtained from these specimens is in the range from 10 to 17 foot-pounds. Impact tests at -40 F usually are about 2 foot-pounds less than at room temperature for the cast maraging steels. Development of casting data is of interest because of the possibility of casting end closures for missile motor cases.

Charpy impact data also have been obtained on precracked Charpy specimens. The test data are reported in units of inch-pounds of energy to fracture the specimen per square inch of fractured area. Since the energy expended in fracturing the precracked specimen is indicative of the energy for crack propagation (without requiring a significant amount of energy for crack initiation), the data are more readily correlated with other fracture-toughness data. The data in Table A-28 indicate that the 18Ni (200) grade is substantially tougher than the 18Ni (250) grade for the few heats evaluated by the precracked Charpy technique. This has been confirmed by Lewis[28] based on precracked

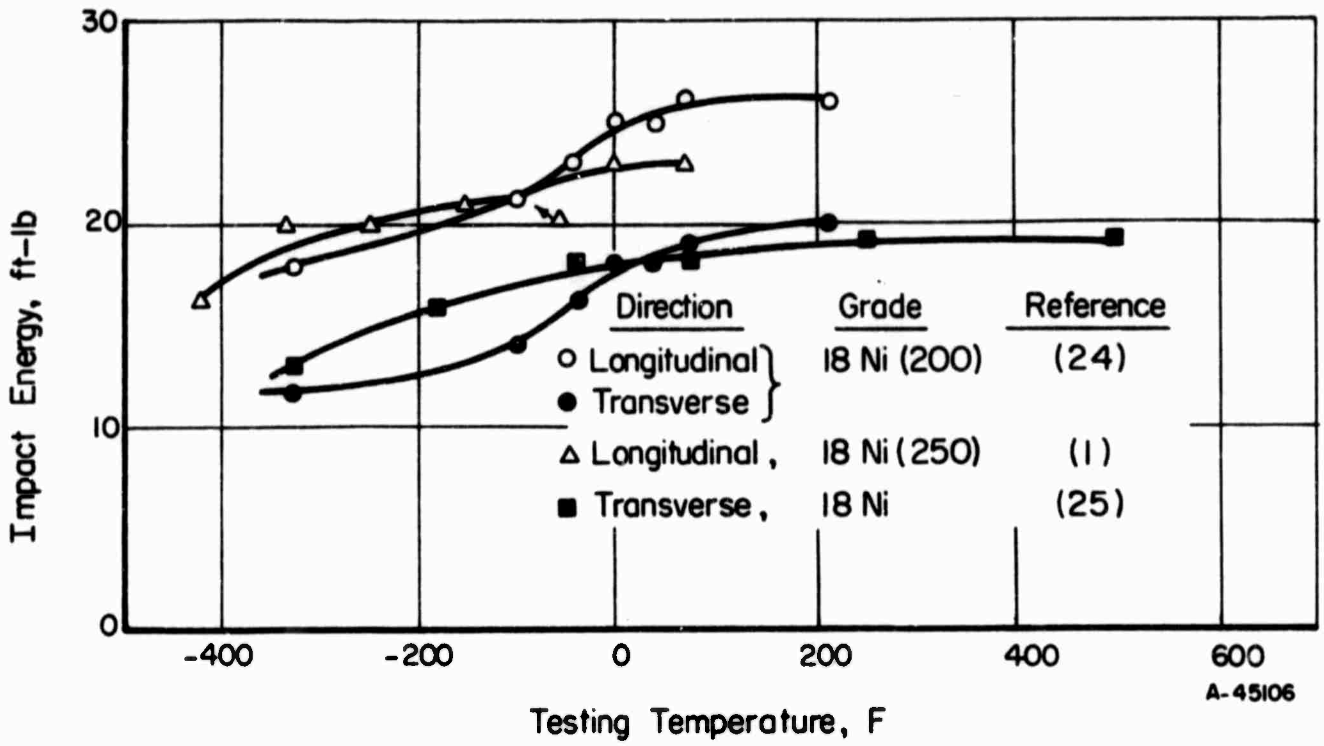


FIGURE 15. CHARPY V-NOTCH IMPACT DATA FOR 18 PER CENT NICKEL MARAGING STEEL PLATE, AS AGED (FROM TABLE A-25)

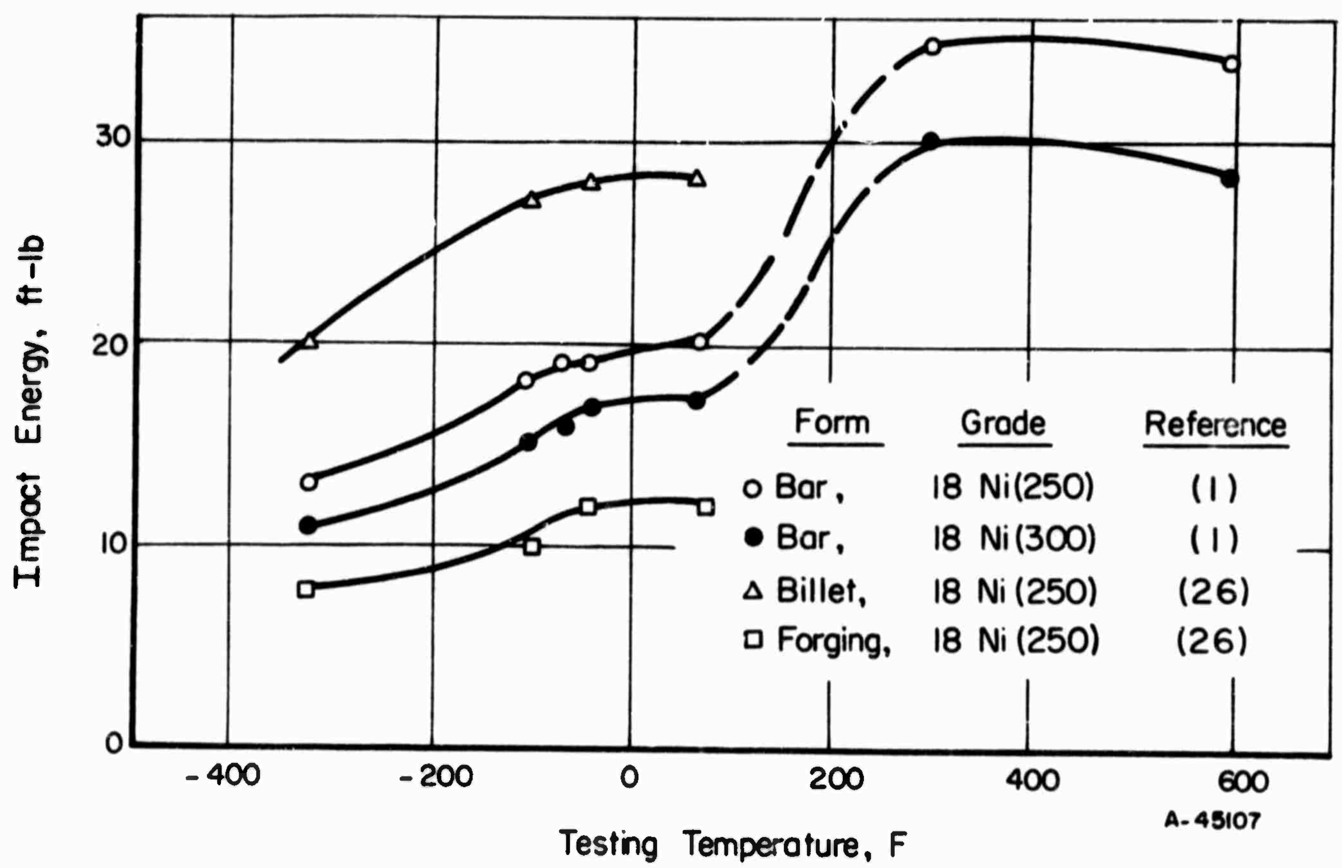


FIGURE 16. CHARPY IMPACT DATA FOR 18 PER CENT NICKEL MARAGING STEEL BAR AND HEAVY SECTIONS, AS AGED (FROM TABLE A-26)

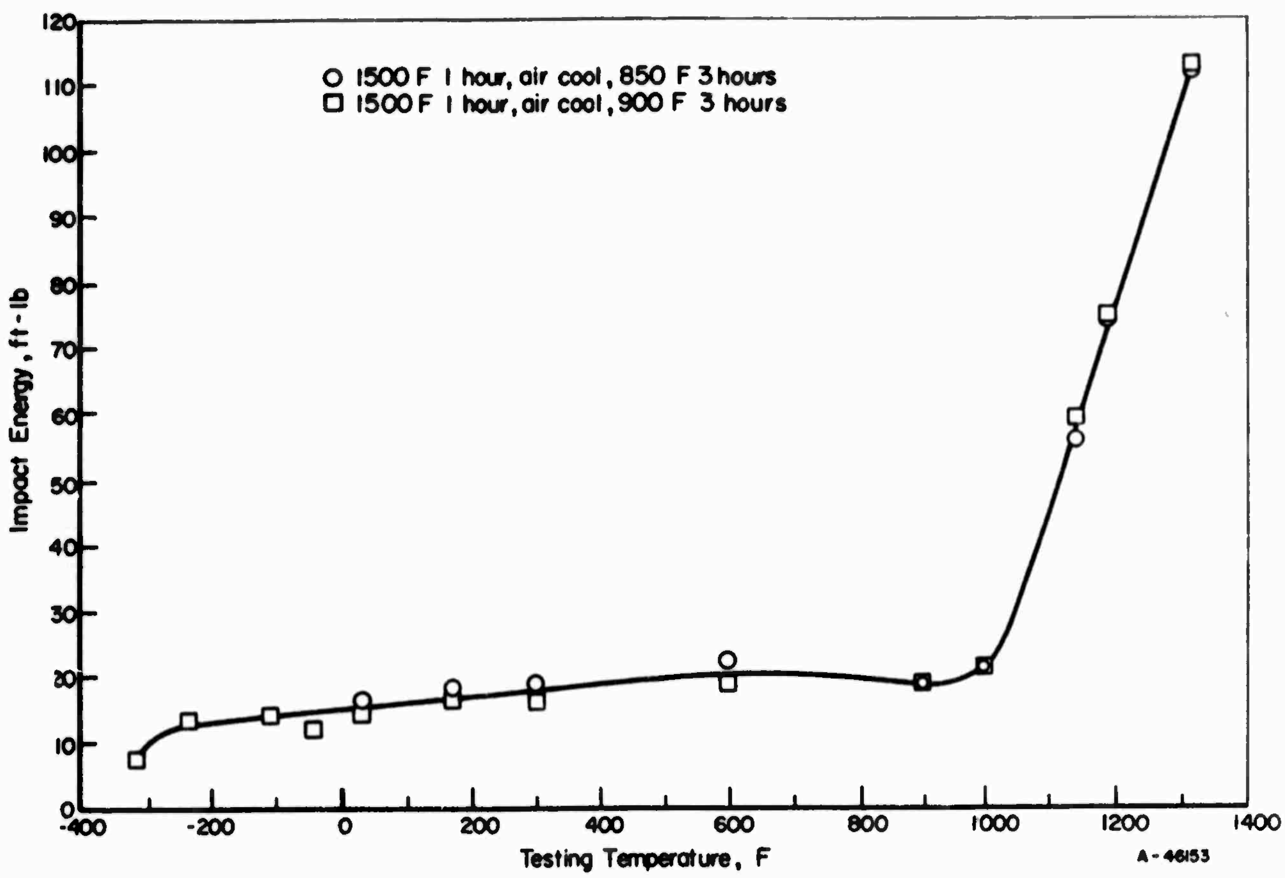


FIGURE 17. CHARPY V-NOTCH IMPACT DATA AT LOW AND ELEVATED TEMPERATURES FOR 18Ni (250) MARAGING STEEL [1/2-INCH PLATE, HEAT A, KULA[27]]

Charpy tests on one heat each of 18Ni (200) grade and 18Ni (250) grade maraging steel. Lewis also pointed out the problem of scatter in data using precracked Charpy specimens, variations in data with variations in crack depth, etc.

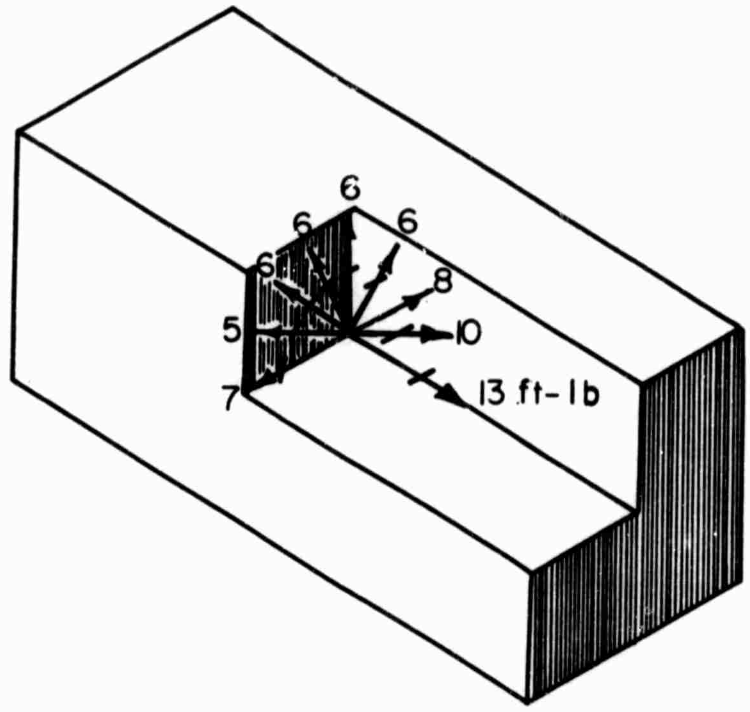


FIGURE 18. EFFECT OF SPECIMEN ORIENTATION ON THE CHARPY IMPACT PROPERTIES OF 4 BY 4-INCH BILLET OF 18Ni (250) MARAGING STEEL CONTAINING 0.007 PER CENT SULPHUR(29)

Arrows indicate specimen axes and short lines indicate direction of the V notches.

Notched Tensile Properties

A number of types of notched tensile specimens have been used in measuring the notched tensile properties or fracture toughness of the maraging steels. Data from some of the recent evaluation programs are presented in this section and in Tables A-29 to A-32 in the Appendix. These programs have been aimed at obtaining some criterion for measuring the relative toughness of the maraging steels. Furthermore, an evaluation of the effects of variations in composition and processing variables is desired as well as comparisons of the toughness parameters with other materials. In general, the maraging steels have better toughness than the competing low-alloy martensitic steels.

The average notched strengths of sharp edge-notched sheet specimens in the longitudinal and transverse directions at various testing temperatures are given in Table A-29. Because of the number of heats involved, variation in specimen specifications, etc., there is considerable scatter in the data. However, from the data, it is possible to observe trends and to note the properties that can be achieved based on the results obtained from the heats that have had the best properties. This approach is taken in reviewing all of the notched-property data.

With the sharp edge-notched NASA-type sheet specimen, the notched strength-tensile strength ratios are over 0.90 for some heats of 18Ni (250) steel at room temperature in the transverse direction. The material referred to had been annealed at 1500 F and air cooled, then aged at 900 F for 3 hours. Reducing the testing temperature to -150 F does not cause a marked change in the notched strength, indicating that the alloy does not become embrittled at this temperature. Increasing the testing temperature to 600 F causes a reduction in the notched strength and a reduction in the notched strength-tensile strength ratio. Cold working followed by aging causes reductions in the notched strengths and in the notched strength-tensile strength ratios. This is more pronounced for transverse specimens than for longitudinal specimens.

For the 0.125-inch-thick sheet specimens that were aged in the as-rolled condition (with no annealing treatment at 1500 F), the notched strengths and notched-strength ratios were unusually low. This was true for the one heat (07249) of 18Ni (250) grade and the one heat (07146) of 18Ni (300) grade. The same effect is noted in data from center-notched specimens from these heats. It is likely that at least one of the factors contributing to the low notched strengths of these heats is the fact that the material was not annealed at 1500 F after rolling.

For data on edge-notched sheet specimens of 18Ni (300) grade in Table A-29, there is one heat with a notched strength-tensile strength ratio as high as 0.98 for longitudinal specimens, while the corresponding ratios for the other heats are 0.80 and less. Transverse specimens of 18Ni (300) grade have lower notched strengths and lower strength ratios than comparable longitudinal specimens. However, the notched strengths are not reduced appreciably in tests at temperatures down to -100 F and up to 300 F. The effect of variations in the composition of Heats 7C056 and 7C057 shows up markedly in the notched properties of specimens from these two heats. The heat on the low side of the composition range has the best notched properties.

The data indicate that the trend for center-notched sheet specimens is similar to that for edge-notched sheet specimens. Several heats (in Table A-30) have notched-strength ratios over 0.90 for both longitudinal and transverse specimens of the (250) grade alloy. Furthermore, the notched properties are only slightly affected by testing temperature over the range from -100 to +300 F.

For the 18Ni (300) grade, the best notched-strength ratios were from 0.70 to 0.76 for longitudinal center-notched specimens tested over the temperature range from -45 to 300 F. Transverse specimens had lower notched strengths and notched-strength ratios than corresponding longitudinal specimens.

The center-notched specimens containing fatigue cracks at the ends of the notches are intended for fracture-toughness evaluation through determination of K_c and K_{Ic} values. Since current studies have shown that center-notched-and-precracked tensile specimens and precracked bend specimens often do not develop a distinct "pop-in" at the point of initial crack propagation, as is the case when other high-strength steels are tested, there is some question as to selection of load to be used in calculating for gross stress in the equation for K_{Ic} (plane strain fracture toughness).[15,30] There is further uncertainty in selection of the load at the point of rapid crack propagation or instability for K_c determination in sheet specimens of the maraging steels. Those who have studied the fracture toughness of the maraging steels have usually defined the methods they have used in selecting the loads for the fracture-toughness calculations. However, the compliance curves (load-deformation curves for notched specimens) for specimens of maraging steels often deviate from a straight line at initiation of crack propagation without indicating a pop-in. An indication of pop-in may occur later in the loading cycle. The significance of the various methods for specifying loads from the compliance curves for the various fracture-toughness parameters for maraging steels has not been established. Thus only limited plane-strain fracture-toughness data for the maraging steels are presented in this report. Considerable effort is being expended to resolve the uncertainties associated with fracture-toughness testing of the maraging steels.

Comparative data by a number of investigators indicate that the maraging steels have greater toughness than any other currently available steels at the same strength levels.[31,32] The problem is the result of trying to establish absolute values of fracture toughness that can be used in calculating critical crack sizes, for establishing minimum toughness specifications, and for developing improved processing techniques leading to even better toughness ratings.

Another type of notched tensile specimen that has been used to evaluate the toughness of maraging steel sheet and plate is the part-through surface-fatigue-cracked specimen. In preparing these specimens, a shallow fatigue crack is produced part way through the thickness and part way across the test section starting at one side in the middle of the test section. In some respects, these fatigue cracks simulate flaws that may occur in pressure vessels and other manufactured parts or components. The immediate purpose of these tests is to determine the effects of the fatigue cracks on the gross stress at fracture, i. e., to determine the load-carrying capacity of the material containing a fatigue crack of a certain size. Under certain conditions, specimens of this type have been used to measure the plane-strain fracture toughness (K_{Ic}) of high-strength alloys (when the depth of the part-through fatigue crack is less than one-half the thickness and when the notched strength is less than about 90 per cent of the yield strength).

The data in Table A-31 in the Appendix indicate that with very small cracks there is no reduction in the notched strength*. As the fatigue-crack sizes are increased, a size is reached which causes lower notch strengths. This trend is illustrated in Figure 19. The largest crack that can be tolerated without causing a reduction in strength of a certain type of specimen of a given material is designated as the "critical crack size" for the part-through fatigue-cracked specimens. The gross stress for fracturing of notched specimens is often calculated in addition to the notched strength, since the gross stress is comparable to the stress calculated for pressure vessels. In addition, one may determine gross stress-density ratios for different materials as is done in Figure 20 to permit a logical comparison of different materials.

In reviewing data on the part-through fatigue-cracked specimens, it will be noted that different parameters are used to designate crack size, e. g., crack length, crack depth, crack area, etc. Thus there has been no agreement on the most logical crack-size parameter to be used for correlation with the notched strength or gross stress in part-through fatigue-cracked specimens. For this reason, all available information on the crack sizes (length, width, and area) are included in Table A-31. Obviously, when using this type of test for several different alloys or for the same alloy subjected to various processing variables, use of a number of specimens with various crack sizes is required in determining the critical crack size. Results of studies of the part-through fatigue-cracked tensile properties of maraging steels are shown in Figures 21, 22, 23, and 24.[33,34,35] The data indicate that there is little, if any, difference in the notched

*Notched strength (maximum load applied in testing a notched specimen to fracture divided by the total cross-sectional area minus the area of the notch) will be used for comparison rather than the gross stress in order to be consistent with the data in the other tables. Net fracture strength is the same as notched strength.

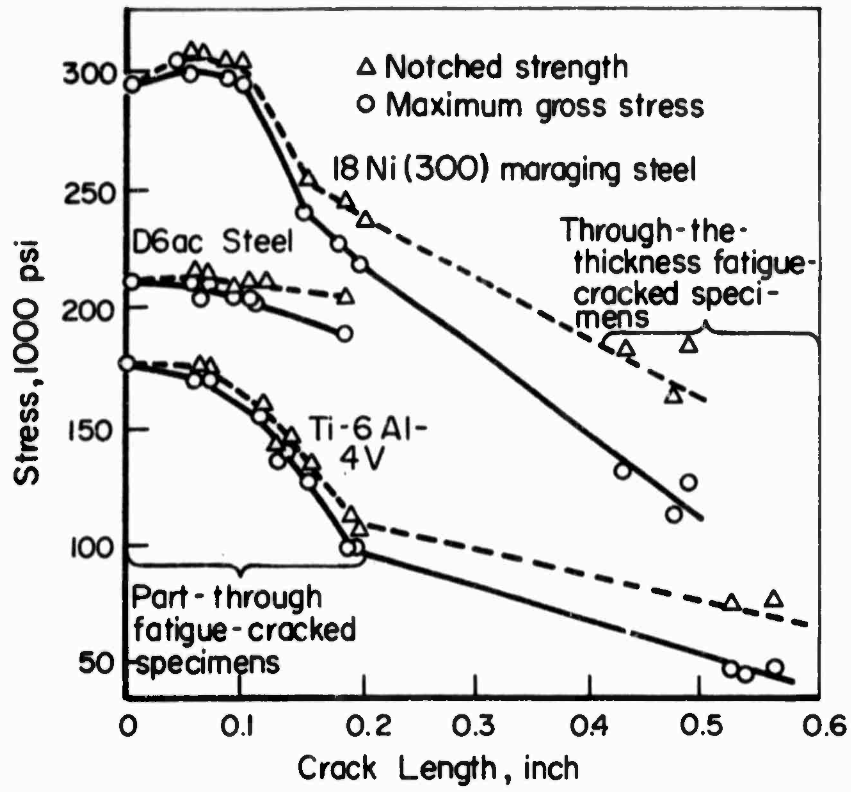


FIGURE 19. TENSILE PROPERTIES OF FATIGUE-CRACKED SPECIMENS OF THREE HIGH-STRENGTH ALLOYS 0.100 INCH THICK(31)

Data for maraging steel specimens are in Table A-31, same reference.

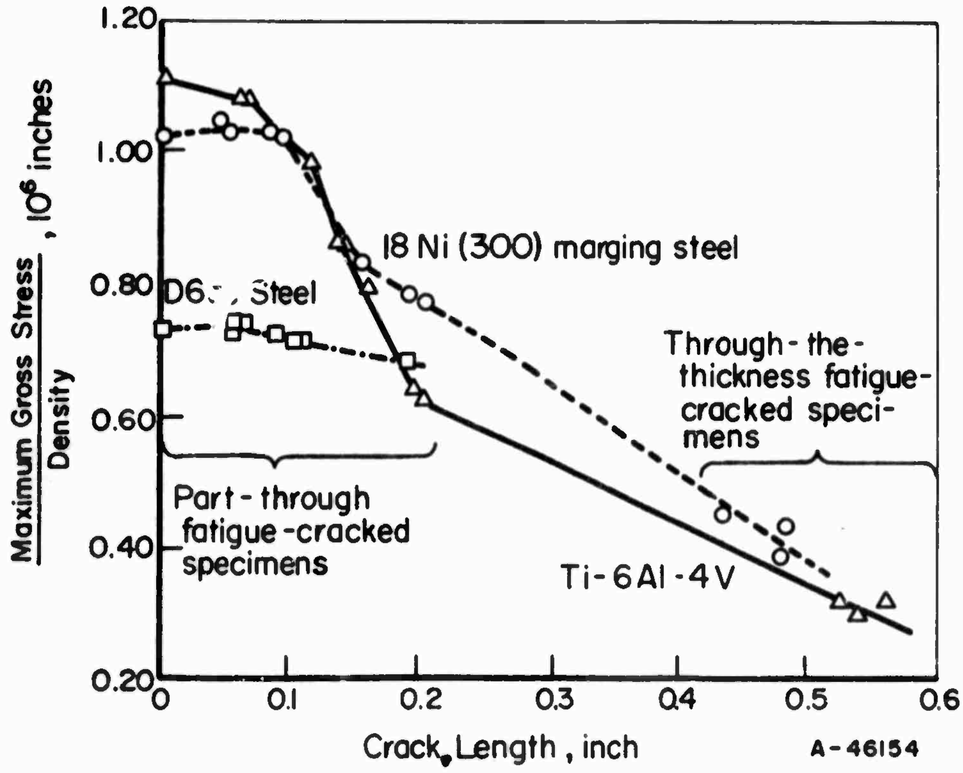


FIGURE 20. GROSS STRESS-DENSITY RATIOS OF FATIGUE-CRACKED SPECIMENS OF THREE HIGH-STRENGTH ALLOYS(31)

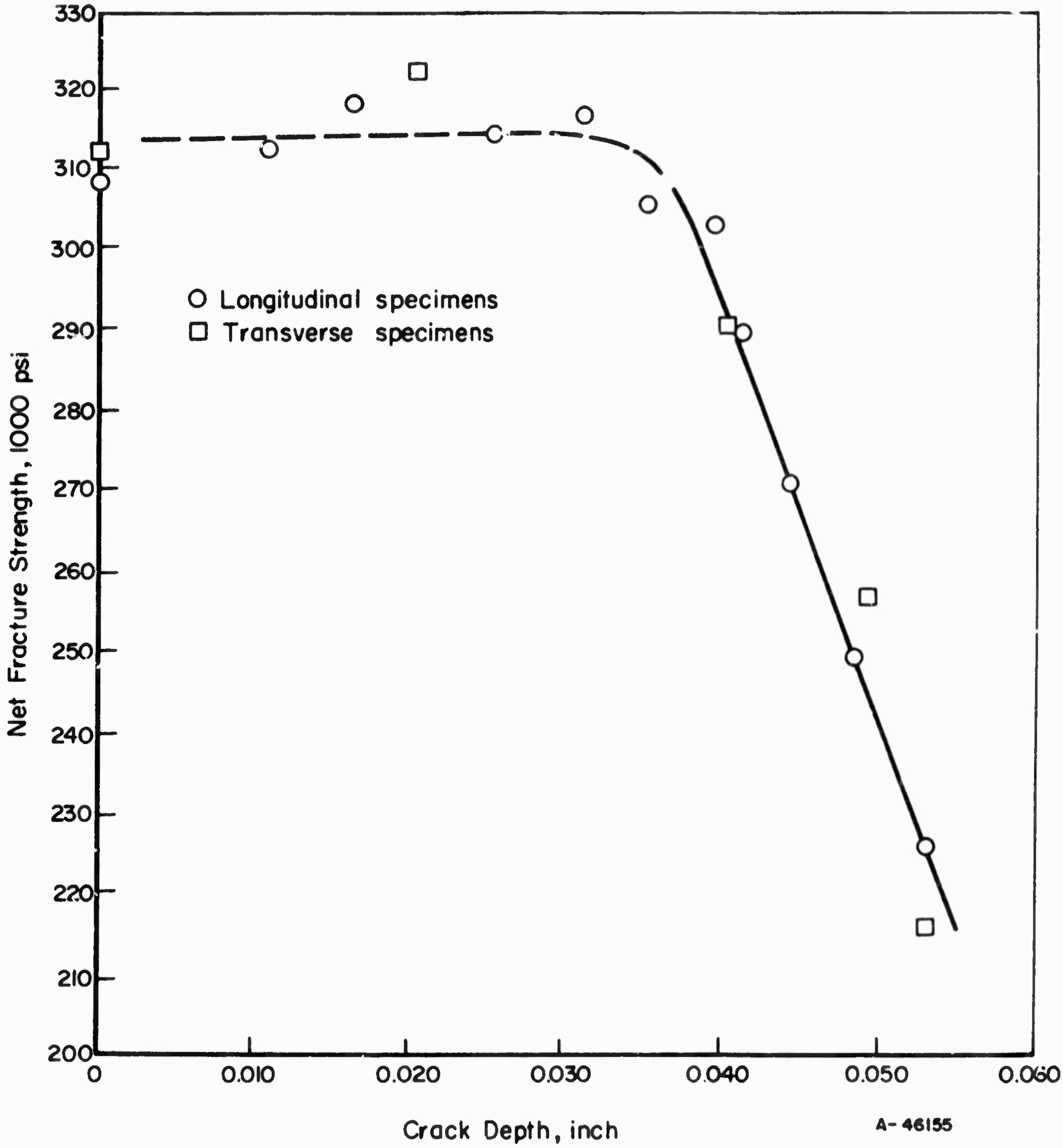


FIGURE 21. NET FRACTURE STRENGTHS OF PART-THROUGH FATIGUE-CRACKED SPECIMENS OF 18Ni (300) MARAGING STEEL SHEET 0.070 INCH THICK(33)

Specimens aged at 900 F for 3 hours. Upper part of curve changed from the original.

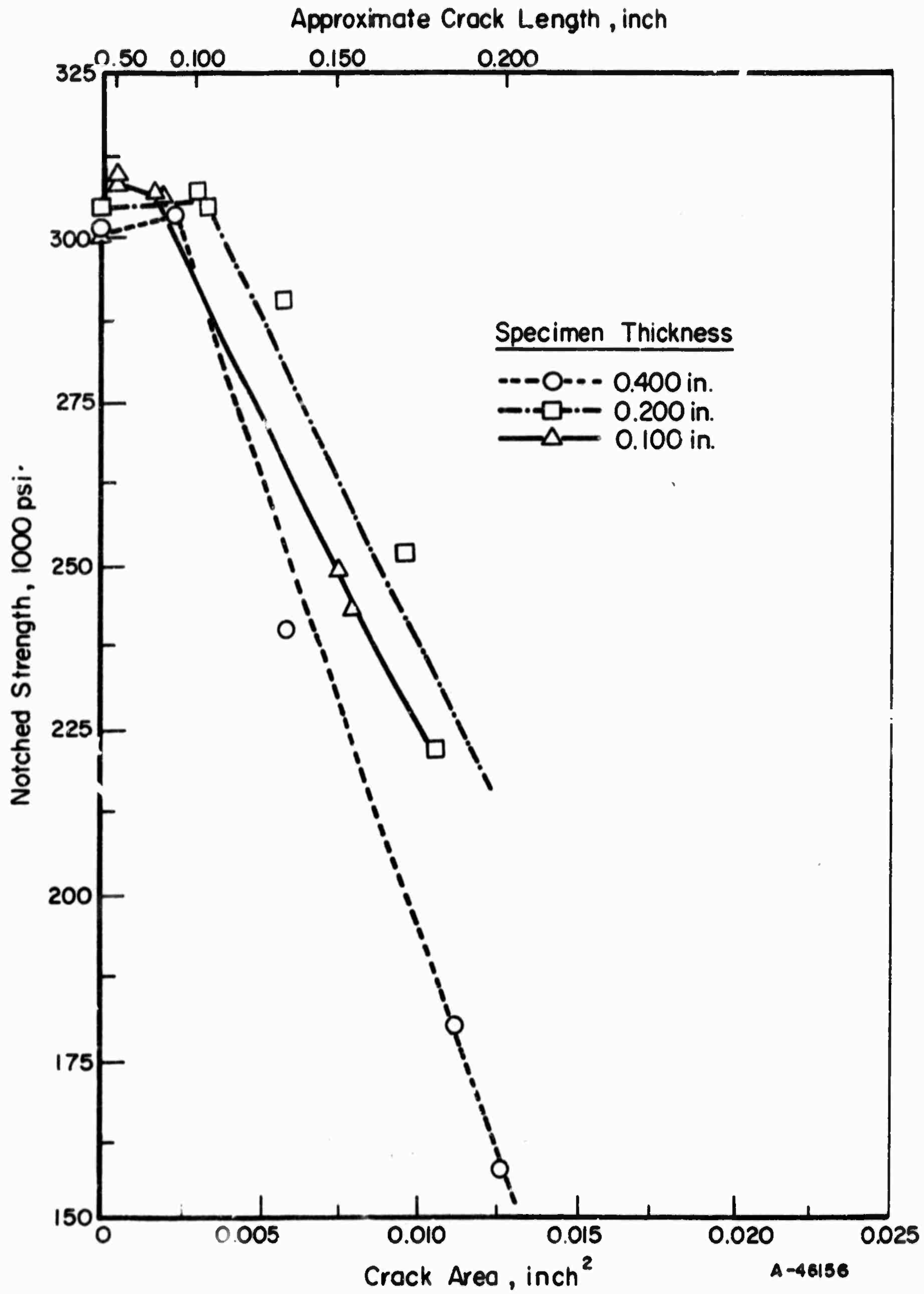


FIGURE 22. NOTCHED STRENGTHS OF PART-THROUGH FATIGUE-CRACKED SPECIMENS OF 18Ni (300) MARAGING STEEL OF THREE THICKNESSES(34)

Data are for longitudinal specimens aged at 900 F for 3 hours (Heat C-40196, 18.55Ni, 9.55Co, 4.70Mo, 0.82Ti).

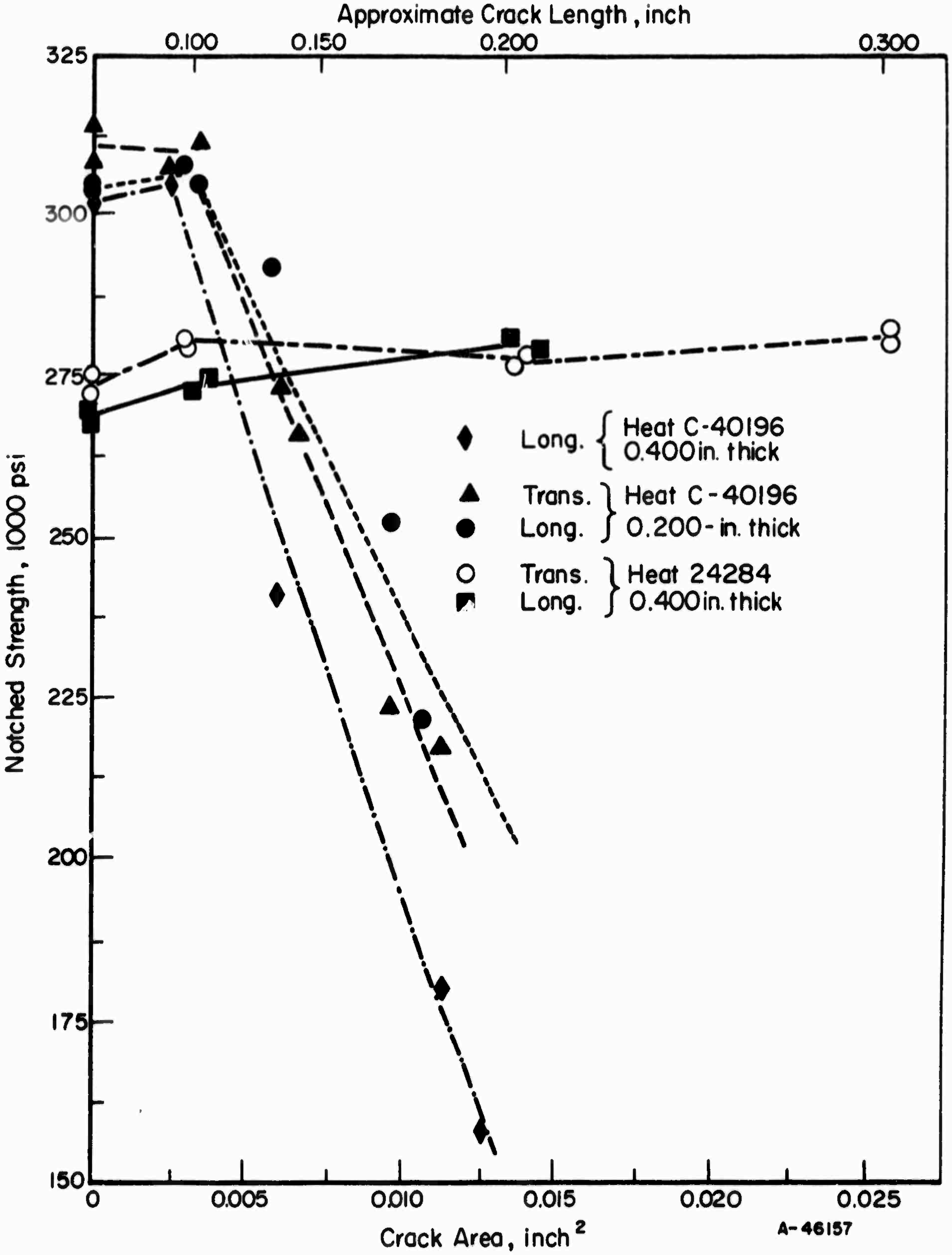


FIGURE 23. NOTCHED STRENGTHS OF PART-THROUGH FATIGUE-CRACKED SPECIMENS OF 18Ni MARAGING STEELS AT TWO STRENGTH LEVELS(34)

Heat Treatment:	1500 F 1 hour, air cooled, 900 F 3 hours, and air cooled.
Heat C-40196:	18.55Ni, 9.55Co, 4.70Mo, 0.82Ti
Heat 24284:	19.00Ni, 9.40Co, 5.00Mo, 0.65Ti.

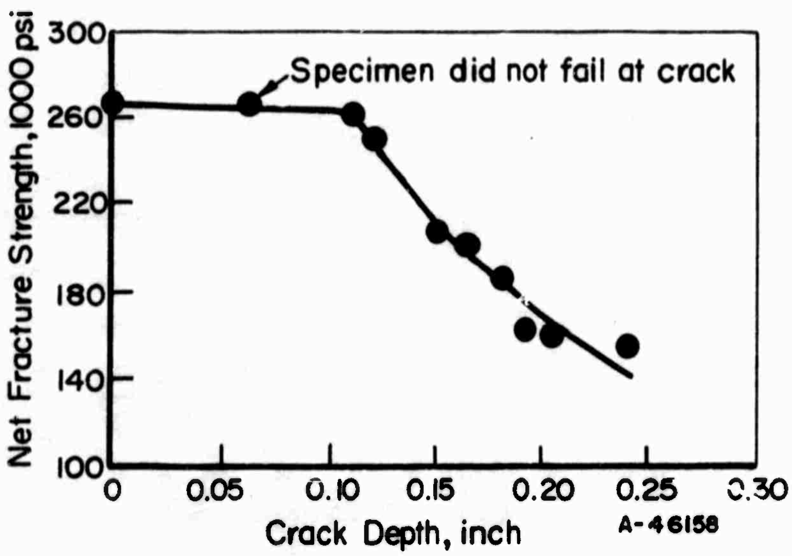


FIGURE 24. NET FRACTURE STRENGTHS OF PART-THROUGH FATIGUE-CRACKED SPECIMENS OF 18Ni (250) MARAGING STEEL PLATE 3/4 INCH THICK(35)

Specimens were 4 by 48 inches and were aged at 900 F for 3 hours.

strengths for comparable specimens taken from longitudinal and transverse directions from the same sheet or plate over the range of sizes of fatigue cracks developed in these specimens. The data plotted in Figure 22 for specimens of three different thicknesses are inconclusive, but the data tend to show the increased sensitivity of the high-strength specimens to very small cracks. However, the strength level of the aged specimens (which is dependent on the hardener content) is a major factor in establishing the relative toughness of the alloy. This is illustrated by the data plotted in Figure 23. The critical crack size for specimens from Heat 24284 at 270,000-psi strength level is considerably larger than for specimens from Heat C-40196 at the 300,000 psi strength level.

Tensile data for round notched specimens from bar, plate, and forgings of 18 per cent nickel maraging steels are presented in Table A-32. It will be noted that there is a considerable spread in the values listed. This spread in properties depends in part on notch concentration factors but also on form, processing procedures, and other variables. In most instances, the longitudinal notched bar specimens with K_t factors to 12 were "notch strengthened" when tested at room temperature. However, for those specimens that were overheated during forging, not annealed before aging, or taken from the short transverse direction, the notched strength-tensile strength ratios were less than unity even for specimens with a K_t factor of 6. 3.

In the data for the notched tensile specimens from forgings (excluding the data on Forging S which was overheated) there is a rather wide scatter in data for specimens with the same K_t factor. It may be speculated that the variations observed in the notched properties reflect the influence of an embrittling phase which has been observed in large forgings of the maraging steels. It is understood that the problem of inconsistent notch properties in specimens from forgings is being extensively investigated.

Notched Bend Tests

Notched tensile data on plate and heavy sections of the 18 per cent nickel maraging steels are being supplemented by notched bend tests. Usually the notched bend specimens have had fatigue cracks at the roots of the notches. The object of the tests has been to obtain plane-strain fracture-toughness data. An advantage of the bend specimens for these studies is that the direction of crack propagation can be controlled by selection of specimen orientation and notch location. Furthermore, the notches can be located in selected positions in weldments in plate. In at least one instance[30], it has been reported that no pop-in was detected in the load-deflection curves for precracked bend specimens of maraging steel. In this instance, preliminary data on plane-strain fracture toughness were based on the loads at which the load-deflection curves deviated from straight lines.

Bend tests on precracked specimens from two 1/2-inch plates of 18Ni (250) maraging steel as reported by Romine[36] usually had straight load-deflection curves to maximum load (except for tests on welds). The plates used in this program were vacuum-arc remelted and cross rolled. The plates were annealed at 1500 F for 1 hour and the specimens from one plate were aged at 900 F for 3 hours and the specimens from the other plate were aged twice at 900 F for 3 hours. K_{Ic} values were 73 to 93 ksi $\sqrt{in.}$ for the two plates and for the four directions of crack propagation studied. The data reported did not include tests on the plate with the cracks propagating in a plane parallel with the surface. This would be equivalent to the fracture path in a tensile specimen for which short transverse data would be obtained.

Because of the advantages in using the precracked notched bend test for measuring the fracture toughness of plate, it is likely that additional data will become available from this type of test in the future.

FATIGUE PROPERTIES

Representative fatigue properties of the 18Ni (250) and the 18Ni (300) grades of maraging steels as bar stock are shown in Figures 25 and 26 for both axial load and rotating beam tests $\left(\text{for R values of 0.02 and -1 respectively, where } R = \frac{\text{minimum stress}}{\text{maximum stress}}\right)$. For the tension-tension (axial) fatigue tests, only two specimens were run out beyond 10^7 cycles, so the data are inconclusive for the endurance limit. However, one specimen of 18Ni (250) grade exceeded 10^7 cycles at a maximum stress level of 48.5 per cent of the tensile strength.

Some of the other points for the 18Ni (250) grade in Figures 25 and 26 also are tagged with the per cent of tensile strength corresponding to the maximum fatigue stress. This permits comparison of the fatigue properties for different heats. In the other figures in this section, the curves represent the low side of the scatter band, based on maximum fatigue stress as per cent of the tensile strength versus the number of cycles to failure.

Unnotched axial and flexural fatigue properties are presented in Figures 27 and 28, respectively, for several material forms. Except for a fatigue-strength advantage shown for forgings which is presently unexplainable, fatigue properties of this steel appear to be relatively little affected by material form. From Figure 27, vacuum-melted material appears to have a definite superiority over air-melted material, based on rather limited data for sheet.

The effects of notch severity and test direction on axial fatigue strength are shown in Figures 29 and 30. Available data for forgings, shown in Figure 29, indicate a moderate superiority in the longitudinal direction; this may be peculiar to the specific test material, since no significant effect of directionality is found for bars at lifetimes exceeding 10^5 cycles, as shown in Figure 30.

In the case of sheet, no notched-fatigue data were found. However, data presented in Figure 31 indicate that pits and other surface defects present in as-rolled sheet act as notches and may lower fatigue strength appreciably.

Limited axial-fatigue data at 650 F are shown for bars in Figure 32. These data indicate fatigue strength between 10^5 and 10^7 cycles is significantly higher at 650 F than at room temperature for both smooth and notched specimens.

The effect of notch severity is re-examined in Figure 33, in which the fatigue-strength reduction factor K_f for each set of notched data is plotted at various lifetimes. Past experience with other alloys, including steels and aluminum alloys, suggests that the maximum value of K_f would be approximately equal to K_t, the stress-concentration factor, and that this value would be reached at around 10^6 cycles. The fact that this is not the case for some of these data suggests they should be used with caution.

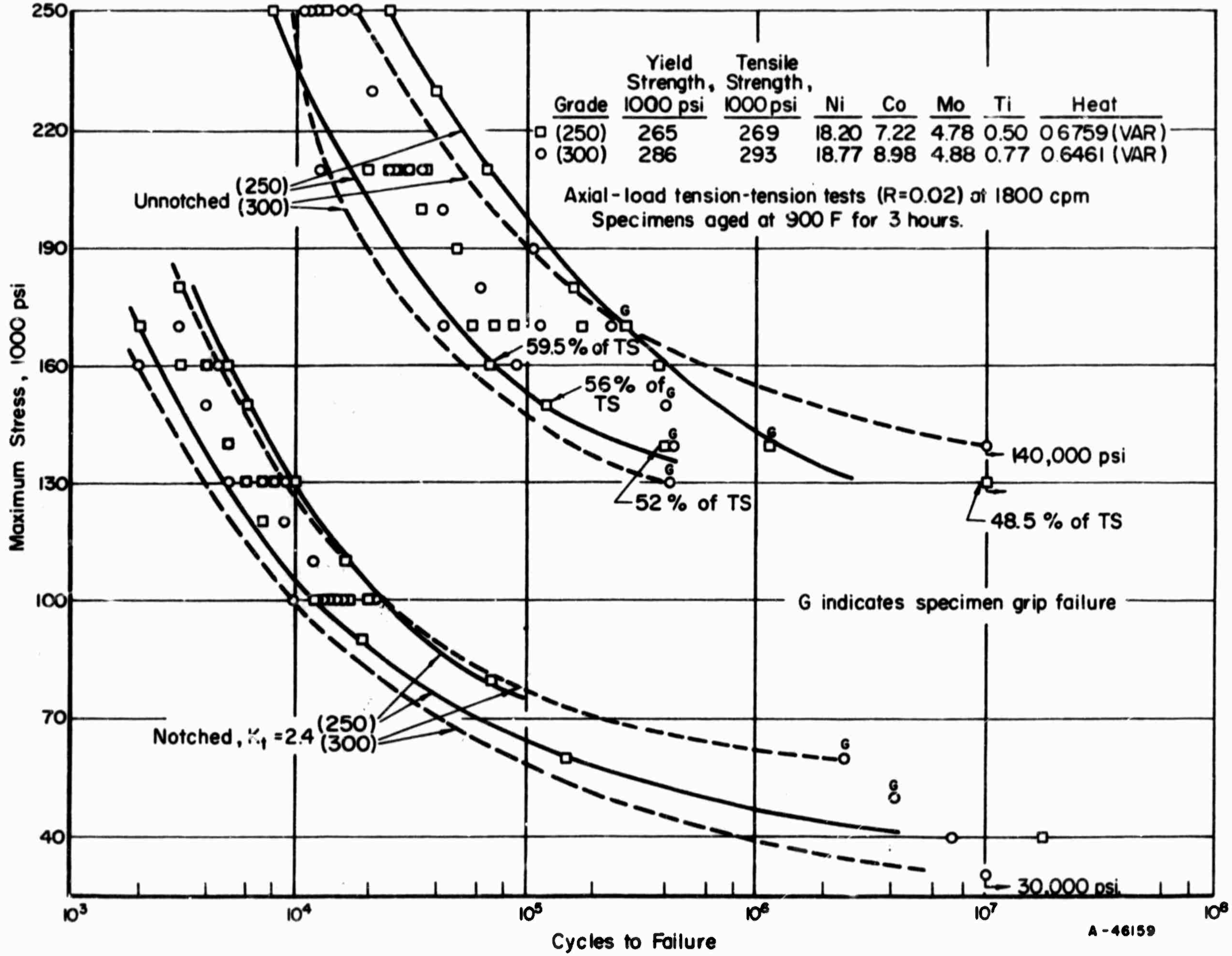


FIGURE 25. FATIGUE CURVES FOR 18Ni (250) AND 18Ni (300) MARAGING STEEL BAR 3/4-INCH DIAMETER FROM AXIAL-LOAD FATIGUE TESTS(23)

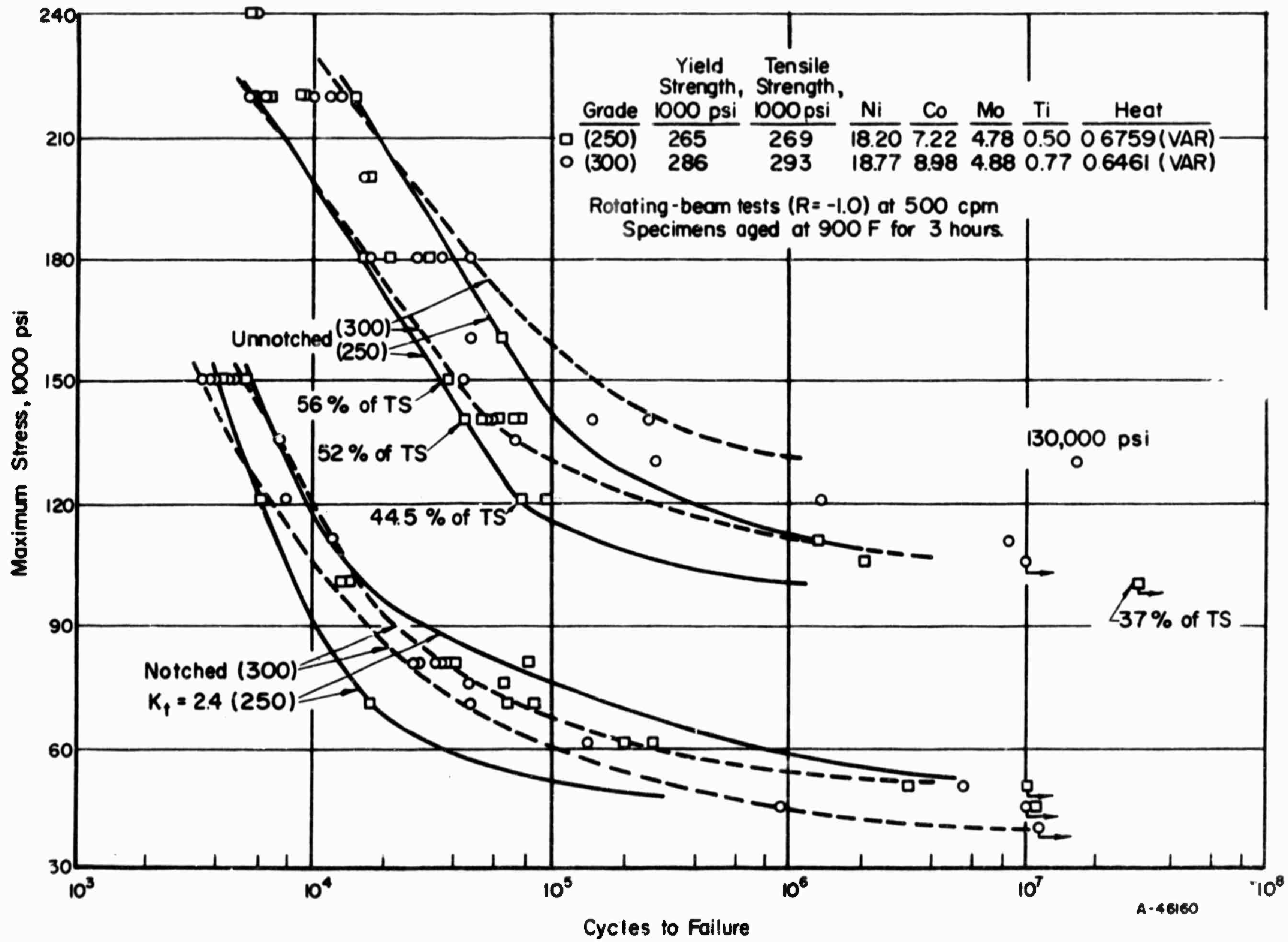


FIGURE 26. FATIGUE CURVES FOR 18Ni (250) AND 18Ni (300) MARAGING STEEL BAR 3/4-INCH DIAMETER FROM ROTATING BEAM FATIGUE TESTS(23)

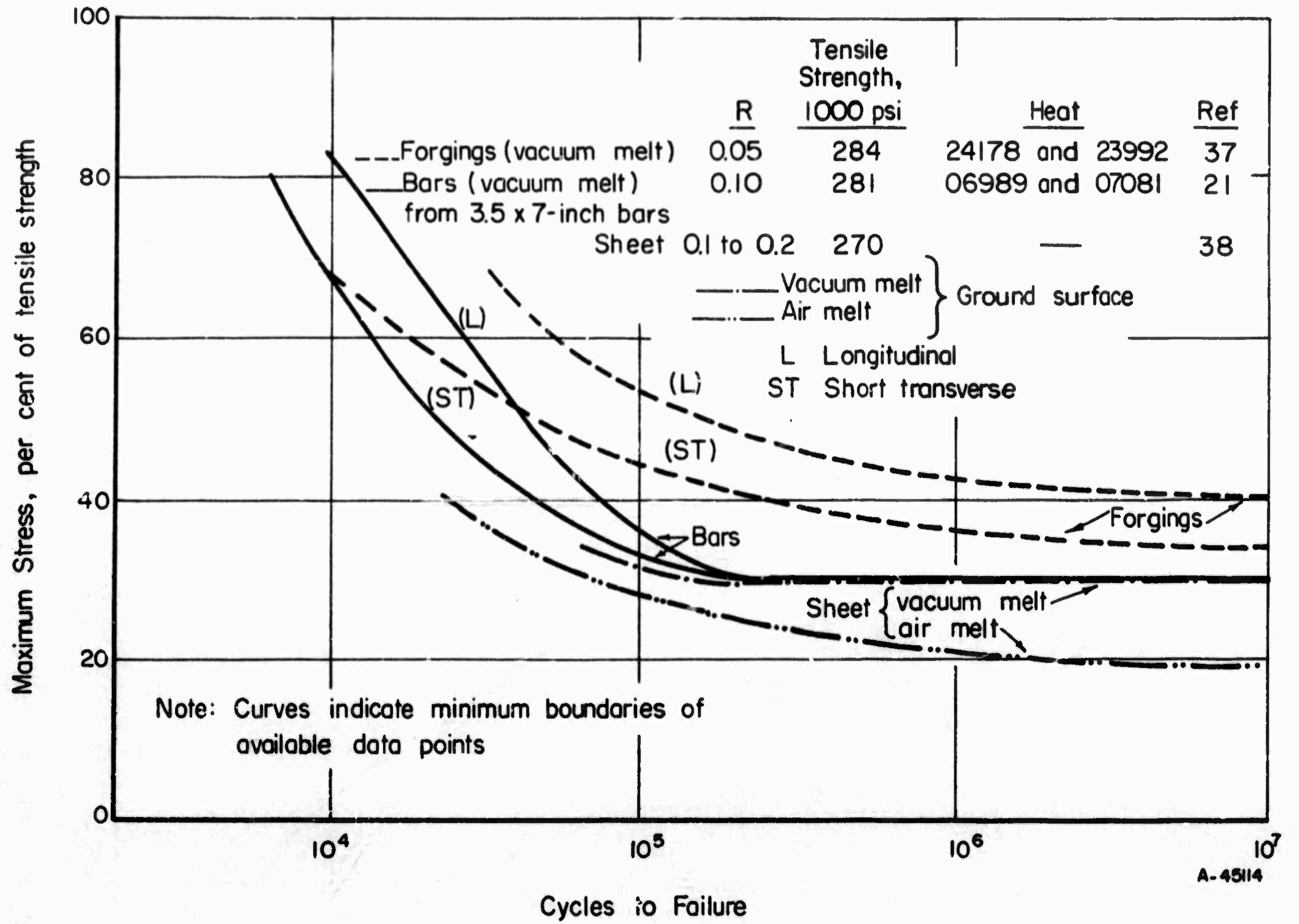


FIGURE 27. EFFECT OF MATERIAL FORM AND MELTING PRACTICE ON UNNOTCHED AXIAL FATIGUE STRENGTH OF 18 PER CENT NICKEL MARAGING STEELS AT ROOM TEMPERATURE

Aged at 900 F for 3 hr.

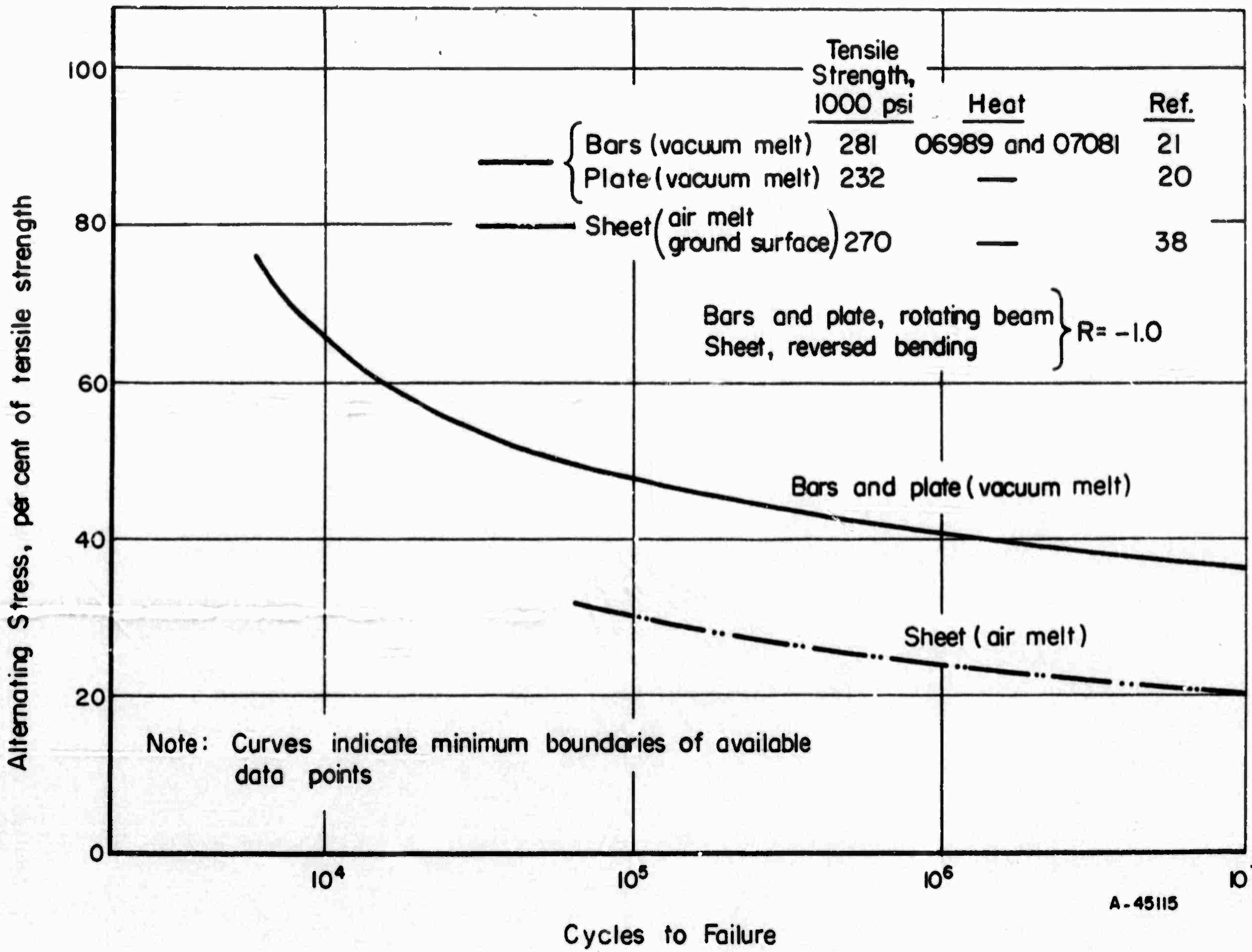


FIGURE 28. EFFECT OF MATERIAL FORM AND MELTING PRACTICE ON UNNOTCHED FLEXURAL FATIGUE STRENGTH OF 18 PER CENT NICKEL MARAGING STEELS AT ROOM TEMPERATURE

Aged at 900 F for 3 hr.

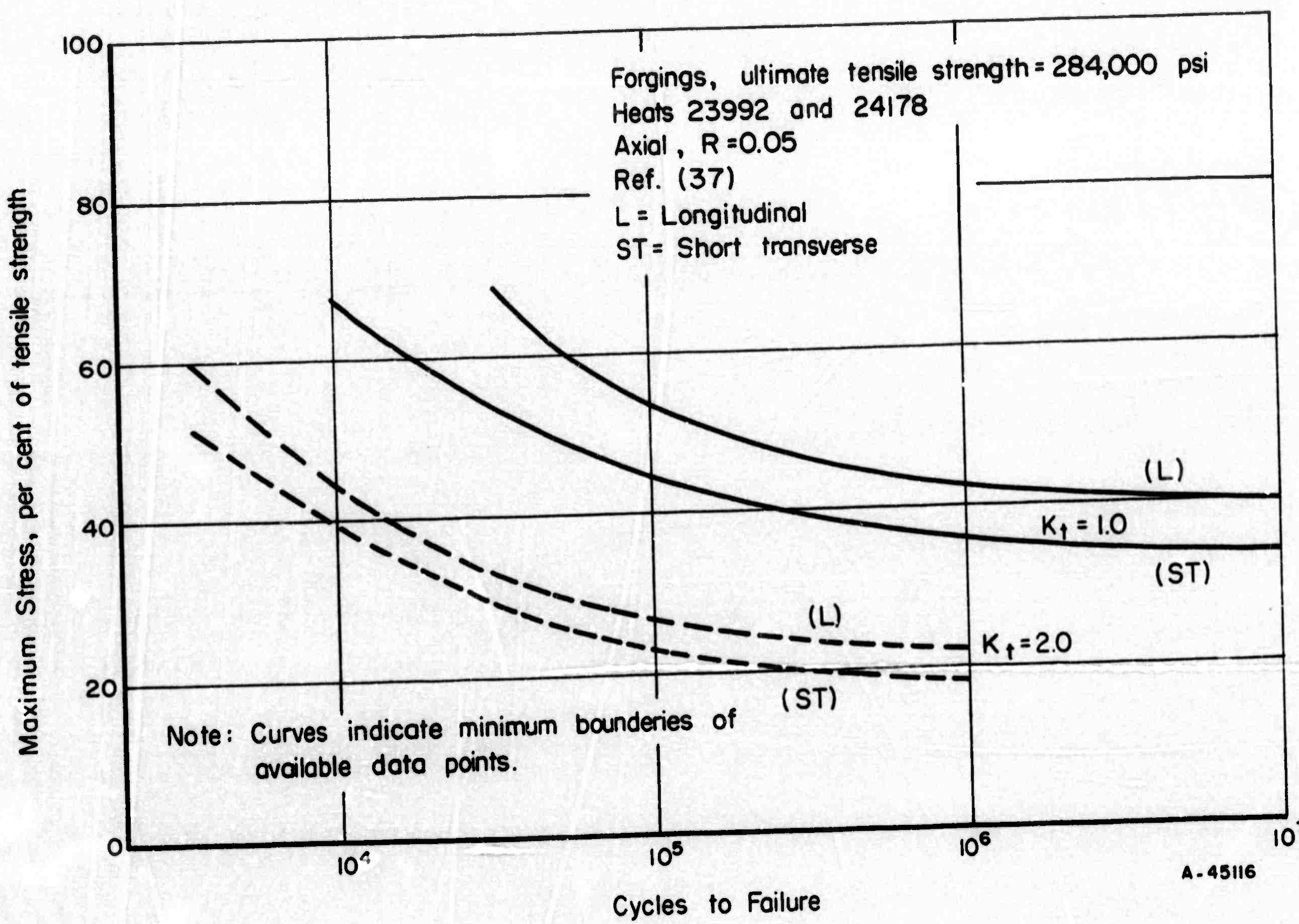


FIGURE 29. EFFECT OF NOTCH SEVERITY AND TEST DIRECTION ON AXIAL FATIGUE STRENGTH OF 18 PER CENT NICKEL MARAGING STEEL FORGINGS AT ROOM TEMPERATURE

Aged at 900 F for 3 hr.

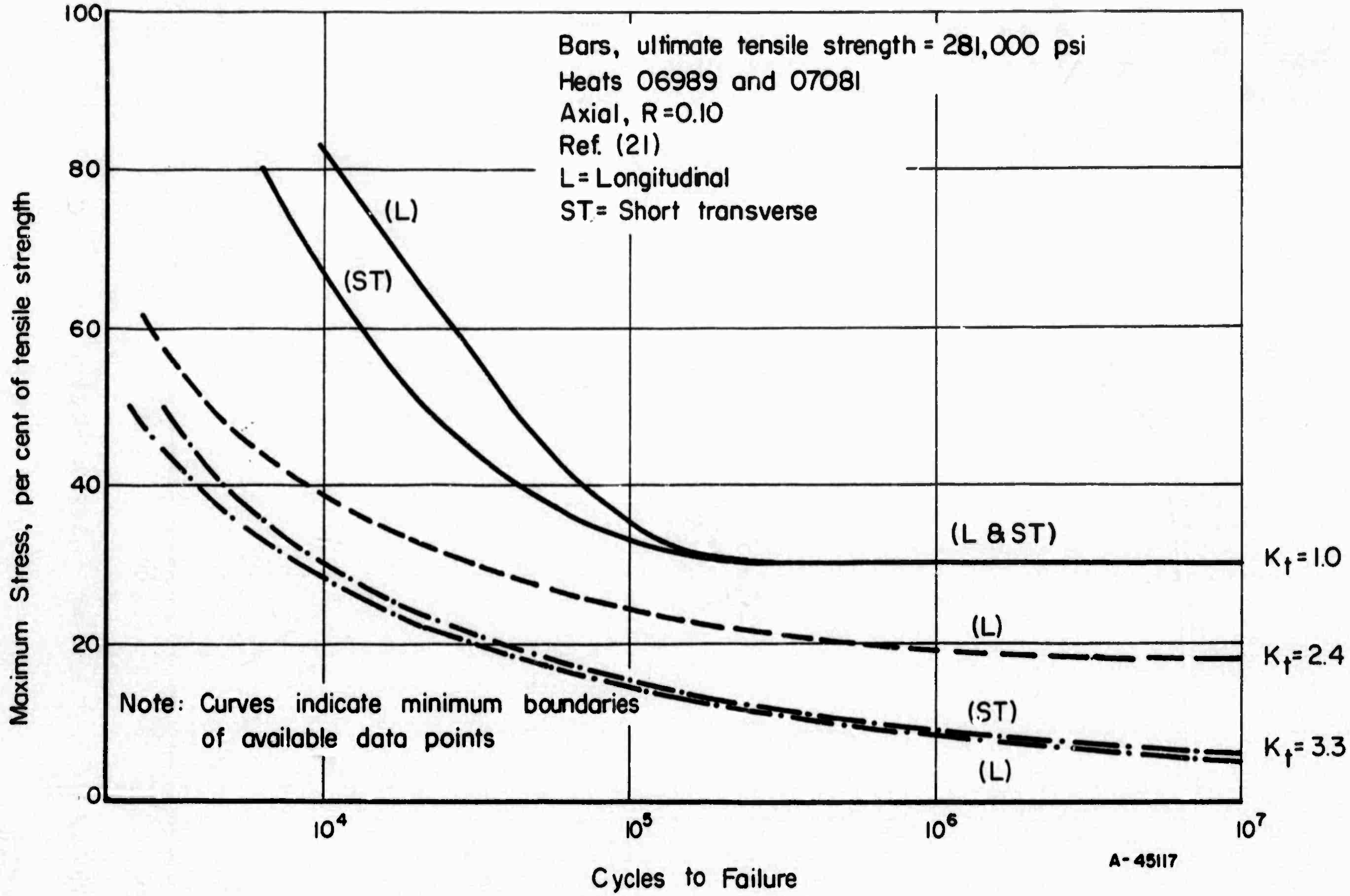


FIGURE 30. EFFECT OF NOTCH SEVERITY AND TEST DIRECTION ON AXIAL FATIGUE STRENGTH OF 18 PER CENT NICKEL MARAGING STEEL BARS AT ROOM TEMPERATURE

Aged at 900 F for 3 hr.

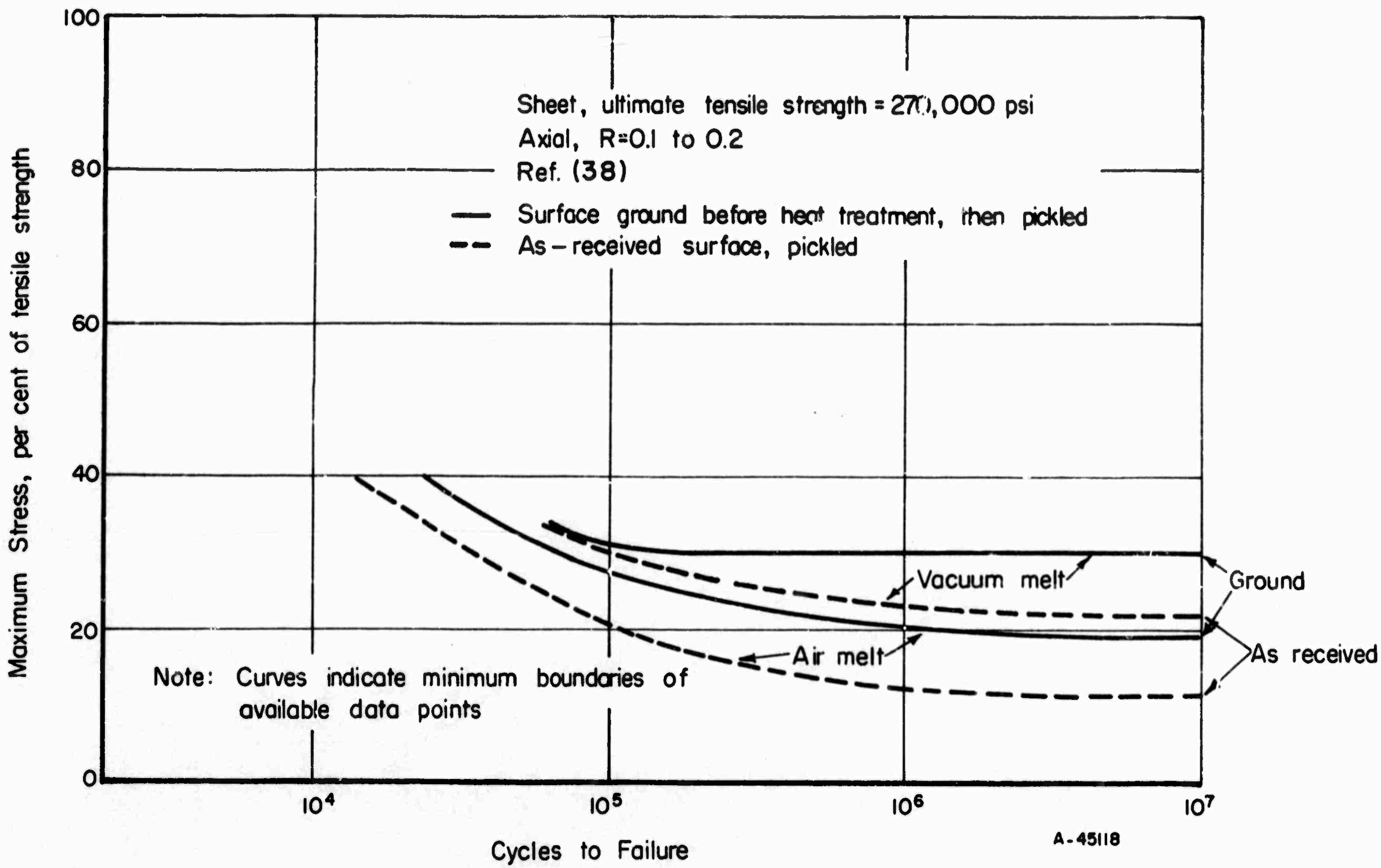


FIGURE 31. EFFECT OF SURFACE CONDITION ON AXIAL FATIGUE STRENGTH OF 18 PER CENT NICKEL MARAGING STEEL SHEET AT ROOM TEMPERATURE

Aged at 900 F for 3 hr.

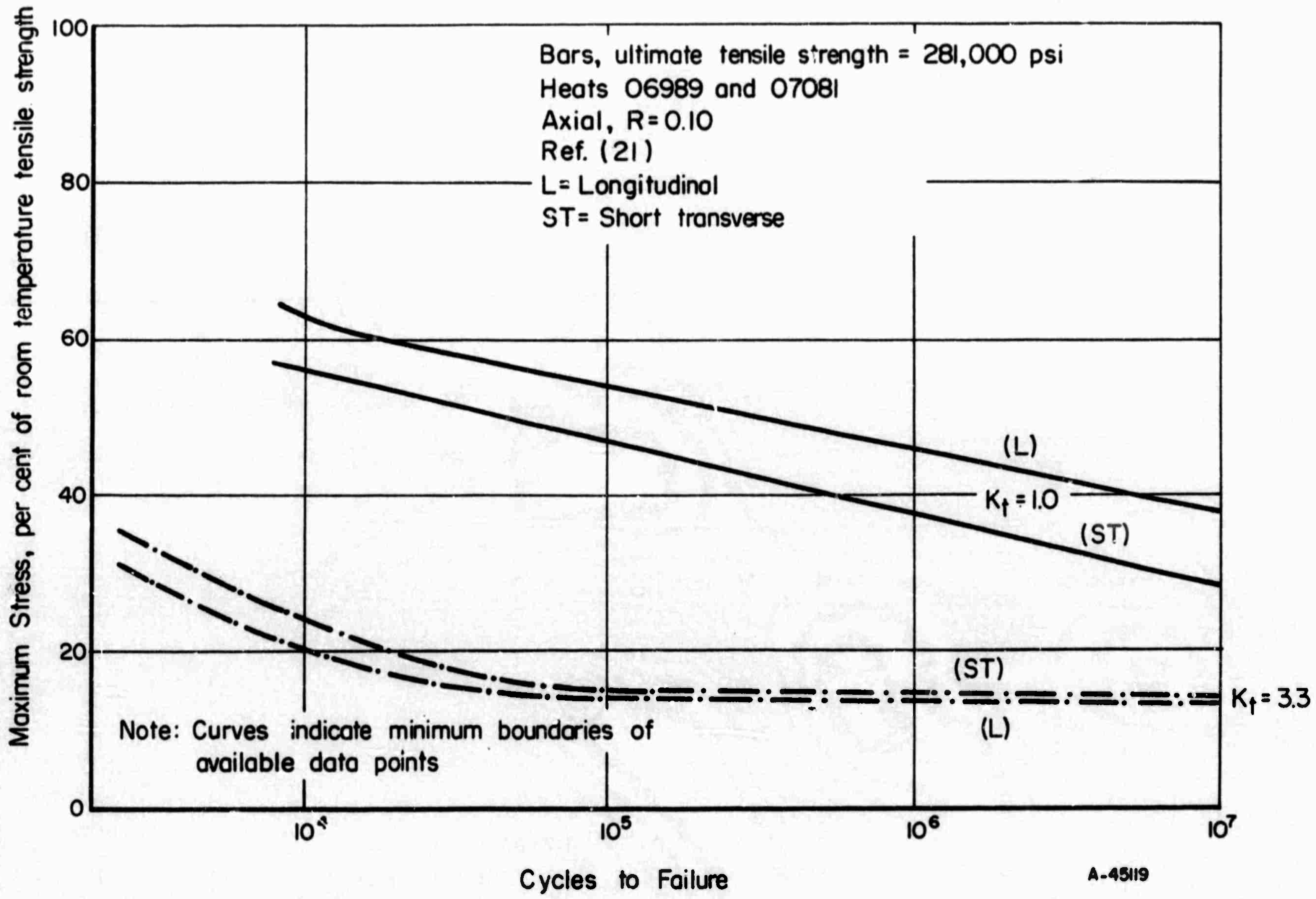


FIGURE 32. EFFECT OF NOTCH SEVERITY AND TEST DIRECTION ON AXIAL FATIGUE STRENGTH OF 18 PER CENT NICKEL MARAGING STEEL BARS AT 650 F

Aged at 900 F for 3 hr.

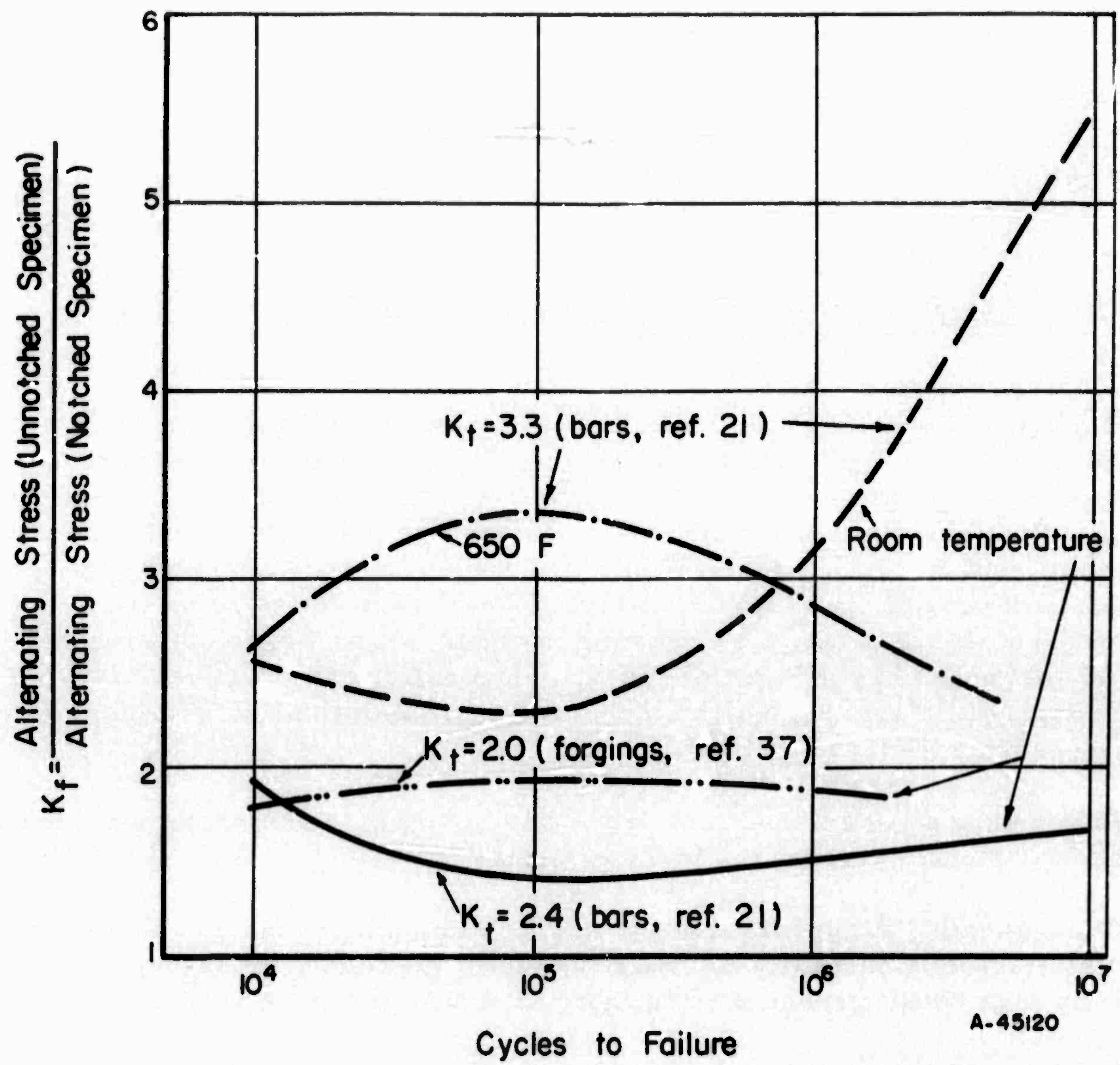


FIGURE 33. FATIGUE-STRENGTH REDUCTION FACTORS FOR NOTCHED 18 PER CENT NICKEL MARAGING STEEL BARS AND FORGINGS

Aged at 900 F for 3 hours.

CREEP AND RUPTURE STRENGTH

Very limited creep and rupture data have been reported for the 18 nickel maraging steels. In this review, these data have been nondimensionalized to eliminate strength as a variable. In this way they can be correlated by means of the Larson-Miller parameter plot, as shown in Table 13. Smooth curves are shown drawn through the correlated data points in Figure 34. In view of the limited quantity of data and relatively high degree of scatter, these values should be considered indicative, but not necessarily typical, of the creep and rupture properties of these steels.

A modified composition of the maraging steels has been developed for improved high-temperature stability.(22) Stress-rupture data for this alloy which contains 15.2 per cent nickel are presented in Table 14 and in Figure 35.

PROPERTIES OF PRESSURE VESSELS OF MARAGING STEELS

Many of the projected applications for maraging steels involve their use as pressure vessels such as lightweight storage vessels for high-pressure gases and solid-propellant rocket-motor cases. The ultimate test to determine the feasibility of the maraging steels for these applications is to fabricate subscale or full-scale vessels and burst them. This has been done to a limited extent, and available data are presented in Table 15. Diameters of vessels range from 2 inches to full-size missile cases. With but one exception the burst stress-tensile strength ratios were 1.05 or greater. This indicates that under biaxial loading the alloy has sufficient toughness to take at least partial advantage of the theoretical increase in strength that is associated with 2:1 biaxial stressing.

Based on available burst-test data, the only other commercial steel which has exceeded 330,000-psi burst stress is Type H-11(46).

Consequently, it appears that, in addition to such advantages as simple heat treatment, satisfactory weldability for many applications, etc., the maraging steels have potentially high burst strengths when fabricated into pressure vessels.

In tests on a series of pressure vessels of a number of high-strength steels, small part-through cracks were intentionally produced in the shells of the vessels.(47) After the vessels were burst tested, a correlation was made between crack depth as per cent of wall thickness and burst stress. The pressure vessels of the maraging steels had higher burst stresses for given crack depths than any of the other steels according to preliminary data.

Fabrication of pressure vessels requires welding of closures and other components to complete the vessels. The mechanical properties of the welds themselves are a very important aspect to consider in selection of the material and fabrication program. This subject is reviewed in Defense Metals Information Center Memorandum 182 dated October 16, 1963.

TABLE 13. CREEP AND RUPTURE STRENGTHS OF 18 PER CENT NICKEL MARAGING STEELS

(Aged 900 F for 3 hours)

Temp, F	Stress, 1000 Psi	Stress, Per Cent[a]	0.1 Per Cent Creep, Hr	0.1 Per Cent Creep, P[b]	0.2 Per Cent Creep, Hr	0.2 Per Cent Creep, P	1 Per Cent Creep, Hr	1 Per Cent Creep, P	Rupture, Hr	Rupture, P
				Laboratory Heat, (250) Grade[c][39]						
800	175	67	--		--		--		38	27.2
800	150	57	--		--		--		561	28.6
900	150	57	--		--		--		6.7	28.3
900	125	48	--		--		--		38	29.4
1000	100	38	--		--		--		4.6	30.2
1000	75	29	--		--		--		48	31.7
				Heat 23832, (250) Grade[40]						
1000	75	29	--		--		--		244	32.7
				Heats 06989 and 07081, (300) Grade[21]						
650	180	64	1700	25.8	--		--		--	
	180	64	1500	25.7	--		--		--	
	217	77	55	24.1	500	25.2	--		--	
	208	74	30	23.8	600	25.3	--		--	
800	110	39	70	27.5	200	28.1	1300	29.1	--	
	110	39	80	27.6	200	28.1	1200	29.1	--	
	115	41	55	27.4	190	28.1	1200	29.1	--	
	115	41	90	27.7	250	28.2	1200	29.1	--	
	150	53	10	26.5	40	27.2	320	28.4	--	
	150	53	15	26.7	60	27.4	380	28.4	--	
	180	64	1.4	25.4	5	26.1	70	27.5	--	
	180	64	1.9	25.5	8	26.3	110	27.8	277	28.3
				Heat 23831, (300) Grade[40]						
800	175	61	--		--		--		522	28.6
1000	75	26	--		--		--		226	32.7

(a) Per cent of ultimate tensile strength at room temperature.
(b) Lason-Miller parameter $P = (T + 460)(20 + \log t) \times 10^{-3}$, where T is temperature in degrees F and t is time in hours.
(c) 19.15Ni, 7.0Co, 4.9Mo, and 0.41Ti:

Heat	Ni	Co	Mo	Ti
23832	18.34	7.69	5.20	0.45
06989	18.62	8.74	4.75	0.63
07081	18.61	9.14	4.72	0.58
23831	18.20	9.05	4.84	0.69

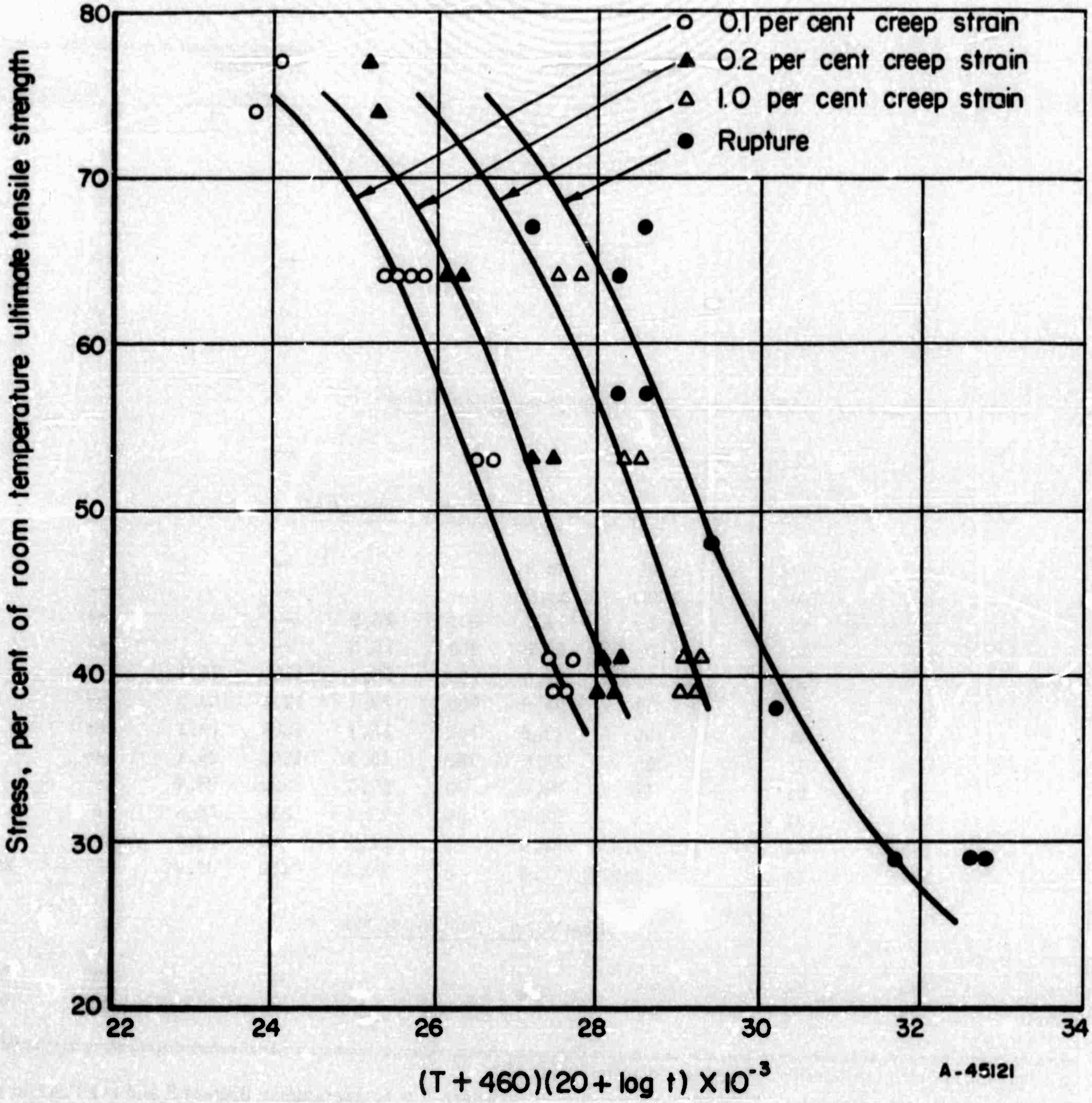


FIGURE 34. CREEP AND RUPTURE STRENGTHS OF 18 PER CENT NICKEL MARAGING STEELS[21,40,39]

Aged at 900 F for 3 hours.

TABLE 14. STRESS-RUPTURE PROPERTIES OF 15 PER CENT NICKEL MARAGING STEEL AS 3/4-INCH BAR[22]

(Specimens annealed at 1800 F, air cooled, and aged at 900 F for 3 hours.)

Temperature, F	Stress, 1000 Psi	Stress, Per Cent[a]	Rupture Life, hours	L-M Parameter[b]	Elongation, per cent
800	220	73	834	28.9	5
800	240	80	292	28.4	8
900	125	42	756	31.2	8
900	150	50	302	30.6	7
900	175	58	95	29.9	10
900	200	67	35	29.3	9
1000	80	27	433	33.1	7
1000	90	30	187	32.5	9
1000	100	33	104	32.2	10
1000	125	42	29	31.3	12

(a) Per cent of ultimate tensile strength at room temperature. The tensile strength at room temperature is 300,000 psi.
(b) Larson-Miller parameter.

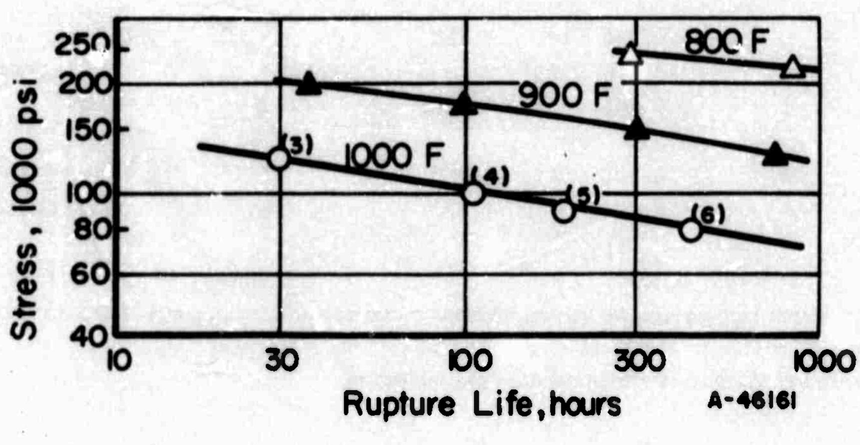


FIGURE 35. STRESS-RUPTURE CURVES FOR 15 PER CENT NICKEL MARAGING STEEL AS 3/4-INCH BAR[22]

The heat treatment and composition are the same as in Table 14. Numbers in parentheses are for the per cent austenite in the test section after rupture.

TABLE 15. BURST TEST DATA ON 18 PER CENT NICKEL MARAGING STEEL PRESSURE VESSELS

Maraging Steel Grade	Vessel	Vessel Dimensions: Diameter, inches	Vessel Dimensions: Wall Thickness, inch	Burst Hoop Stress, 1000 psi	Burst Stress-Tensile Strength Ratio	Fabrication Method	References
(250)	0103	(Typhon missile)		272	1.05	Flow turned, annealed, closures	41
	0203	(Typhon missile)		281	1.05	welded on, aged 900 F 3 hr	
(300)	PV #1	2	0.047	346	1.20	Drawn, annealed, welded, aged	43
	PV #2	2	0.047	374	1.30	Drawn, welded, aged	
	PV #4	2	0.040	362	1.27	Drawn, annealed, welded, aged (one drawn cup 18-9-5 composition, the other 18-8-5)	
(300)	1	6	--	338	1.16	Forged, machined, HT[a]	42
	2	6	--	342	1.18	Ditto	
	3	6	--	323	1.11	Forged, machined, girth welded,	
	4	6	--	338	1.16	HT	
	5	6	--	344	1.18	Shear-spun, HT, cold worked	
	6	6	--	298	(b)	Shear-spun, girth welded, HT	
	7	6	--	358	1.19	Shear-spun, HT	
	8	6	--	350	1.14	Shear-spun, HT	
(300)	2	6	0.140	336	1.07	Drawn (seamless), 1500 F 1 hr,	44
	3	6	0.140	330	1.05	air cooled, aged 900 F	
	6	6	0.140	349	1.11	3 hr	
(300)	S/N 1	24	0.130	328	1.13	Flow turned, annealed, girth	34
	S/N 2	24	0.130	328	1.13	welded, aged 900 F 3 hr	
(300)	--	(Pershing case)		342	1.19	--	45

(a) HT = heat treated.
(b) Vessel failed prematurely; fracture initiated at weld undercut.

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APPENDIX

PROPERTY DATA

TABLE A-1. COMPOSITIONS OF HEATS OF 18Ni (250) MARAGING STEEL SHOWN IN FIGURE 5[5]

Heat	Size of Heat, pounds	Melting Method	Composition, per cent												
			C	Mn	P	S	Si	Ni	Mo	Co	Ti	Al	B	Zr	Ca
06137	1,000	VAR	0.01	0.11	0.007	0.004	0.07	18.2	4.8	7.6	0.42	0.09	0.004	--	0.05[a]
23664	1,000	VAR	0.016	0.05	0.002	0.007	0.06	18.2	4.8	8.0	0.37	0.09	0.004	0.01	0.05[a]
40059	4,000	VAR	0.03	0.03	0.003	0.006	0.03	19.1	4.4	8.2	0.40	0.04	0.003	0.02	0.05[a]
84625	19,000	Air arc	0.026	0.010	0.008	0.010	0.064	18.7	4.59	7.87	0.24	0.085	0.003[a]	0.01	--
A6824	1,000	Air ind.	0.02	0.11	0.007	0.007	0.09	18.54	5.34	7.38	0.44	0.095	0.003[a]	0.01[a]	0.06[a]
A6939	1,000	Air ind.	0.03	0.15	0.004	0.013	0.09	18.2	4.7	7.4	0.35	0.005	0.002	--	0.05[a]
X51623	25,000	Air arc	0.026	0.05	0.003	0.010	0.09	18.34	4.62	7.61	0.47	0.15	0.003	--	--
X51742	25,000	Air arc	0.022	0.02	0.003	0.008	0.10	17.63	4.80	7.32	0.42	0.079	0.003[a]	--	--

(a) Per cent added.

TABLE A-2. COMPOSITIONS OF HEATS OF 18Ni(300) MARAGING STEEL MADE WITH INTENTIONAL VARIATIONS IN TITANIUM, MOLYBDENUM, AND COBALT[7]

Heat[b]	Composition, per cent[a]							
	C	Mn	Si	Ni	Mo	Co	Ti	Al
RV 477	.018	.002	.006	18.29	4.95	9.10	0.40	0.089
RV 472	.021	.002	.006	18.44	4.95	9.11	0.55	0.027
RV 490	.030	.002	.006	18.50	5.01	9.02	0.71	0.120
RV 475	.023	.004	.007	18.40	4.96	8.99	0.84	0.042
RV 476	.020	.002	.006	18.60	4.90	9.05	1.00	0.078
RV 478	.027	.003	.019	18.46	4.70	8.96	0.55	0.084
RV 472	.021	.002	.009	18.44	4.95	9.11	0.55	0.027
RV 480	.027	.003	.009	18.69	5.30	9.07	0.53	0.093
RV 482	.026	.002	.019	18.26	4.70	9.13	0.71	0.073
RV 490	.030	.002	.019	18.50	5.01	9.02	0.71	0.120
RV 481	.026	.002	.024	18.30	5.19	9.11	0.73	0.065
RV 448	.029	.002	.009	18.51	4.92	8.46	0.52	0.089
RV 472	.021	.002	.009	18.44	4.95	9.11	0.55	0.027
RV 451	.030	.003	.009	18.33	5.05	9.46	0.55	0.049
RV 483	.027	.002	.014	18.51	4.95	8.52	0.71	0.084
RV 490	.030	.002	.019	18.50	5.01	9.02	0.71	0.120
RV 473	.019	.003	.009	18.40	4.95	9.34	0.70	0.044

(a) S and P were less than .010 per cent.

(b) All heats were melted in a vacuum induction furnace and poured into 4-inch square 50-pound ingots. The ingots were press forged to bar and rolled to 0.125-inch strip. The strip was cold rolled to 0.062-inch sheet.

TABLE A-3. ROOM-TEMPERATURE TENSILE PROPERTIES OF 0.062-INCH THICK SHEET MADE FROM THE HEATS LISTED IN TABLE A-2[a](7)

Heat	Chemical Variation	Test Direction	Yield Strength 0.02% Offset, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness, R_C
			Ti Variations				
RV 477	0.40 Ti	L	243	270	272	2.5[b]	53.0
RV 472	0.55 Ti	L	235	272	280	2.5	54.1
RV 490	0.71 Ti	L	214	293	300	3.0	55.2
RV 475	0.84 Ti	L	246	313	314	2.0[b]	56.7
RV 476	1.00 Ti	L	273	307	308	2.0[b]	57.2
RV 477	0.40 Ti	T	246	280	280	3.0[a]	53.0
RV 472	0.55 Ti	T	240	287	287	2.5[b]	54.1
RV 490	0.71 Ti	T	234	299	299	2.5[b]	55.2
RV 475	0.84 Ti	T	241	316	319	2.0[b]	56.7
RV 476	1.00 Ti	T	275	(c)	321	2.0[b]	57.2
			Mo Variations – 0.55 Ti				
RV 478	4.70 Mo	L	244	277	279	2.5	53.6
RV 472	4.95 Mo	L	235	272	280	2.5	54.1
RV 480	5.30 Mo	L	249	(c)	297	2.5[b]	55.0
RV 478	4.70 Mo	T	250	287	287	2.0[b]	53.6
RV 472	4.95 Mo	T	240	287	287	2.5[b]	54.1
RV 480	5.30 Mo	T	262	302	302	2.5	55.0
			Mo Variations – 0.70 Ti				
RV 482	4.70 Mo	L	247	286	289	3.0	54.7
RV 490	5.01 Mo	L	214	293	300	3.0	55.2
RV 481	5.19 Mo	L	252	(c)	299	2.0[b]	56.2
RV 482	4.70 Mo	T	253	(c)	288	2.0	54.7
RV 490	5.01 Mo	T	234	299	299	2.5[b]	55.2
RV 481	5.19 Mo	T	278	(c)	306	2.5	56.2
			Co Variations – 0.55 Ti				
RV 448	8.46 Co	L	232	272	276	2.5[b]	53.3
RV 472	9.11 Co	L	235	272	280	2.5	54.1
RV 450	9.46 Co	L	248	281	284	2.5[b]	54.4
RV 448	8.46 Co	T	244	281	283	2.5[b]	53.3
RV 472	9.11 Co	T	240	287	287	2.5[b]	54.1
RV 450	9.46 Co	T	263	298	298	2.5[b]	54.4

TABLE A-3. (Continued)

Heat	Chemical Variation	Test Direction	Yield Strength 0.02% Offset, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 Inches, per cent	Hardness, R_C
			Co Variations – 0.70 Ti				
RV 483	8.52 Co	L	174	267	280	2.5(b)	54.8
RV 490	9.02 Co	L	214	293	300	3.0	55.2
RV 473	9.34 Co	L	210	287	292	2.0	55.6
RV 483	8.52 Co	T	256	292	293	2.5	54.8
RV 490	9.02 Co	T	234	299	299	2.5(b)	55.2
RV 473	9.34 Co	T	235	294	296	2.0	55.6

(a) Annealed at 1500 F for 10 minutes, air cooled and aged at 900 F for 3 hours and air cooled.

(b) Broke on or outside gage marks.

(c) Fractured before 0.2% YS attained.

TABLE A-4. EFFECTS OF ALLOY CONTENT[(a)] ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF 18Ni (300) MARAGING STEEL IN THE FORM OF 0.062 INCH SHEET, SOLUTION TREATED AT 1500 F FOR 15 MINUTES AND AGED AT 900 F FOR 3 HOURS[(9)]

				Average Mechanical Properties		
Co	Mo	Ti	Rolling Direction	Yield Strength 0.2% Offset, 1000 psi	Tensile Strength, 1000 psi	Elongation in 1 Inch, per cent
9.10	4.95	0.40	L	268	274	5.9
(HT. RV 477)			T	273	279	5.4
8.96	4.70	0.55	L	269	272	5.2
(HT. RV 478)			T	276	282	5.4
8.46	4.92	0.52	L	278	280	5.5
(HT. RV 448)			T	272	279	5.4
9.11	4.95	0.55	L	277	283	5.2
(HT. RV 472)			T	272	281	5.9
9.13	4.70	0.71	L	285	290	5.1
(HT. RV 482)			T	301	303	4.6
9.46	5.05	0.55	L	279	285	5.4
(HT. RV 450)			T	289	294	4.9
8.52	4.95	0.71	L	282	287	5.5
(HT. RV 483)			T	294	295	4.6
9.07	5.30	0.53	L	290	294	5.6
(HT. RV 480)			T	303	308	4.6
9.02	5.01	0.71	L	294	297	5.0
(HT. RV 490)			T	306	307	4.1
9.58	4.92	0.70	L	291	295	5.2
(HT. RV 473?)			T	288	295	5.0
9.11	5.19	0.73	L	306	308	4.9
(HT. RV 481)			T	309	311	5.2
8.99	4.96	0.84	L	308	310	4.6
(HT. RV 475)			T	317	322	4.7
9.05	4.90	1.00	L	322	324	4.4
(HT. RV 476)			T	327	337	4.0

(a) For complete composition of the heats see Table A-2.

TABLE A-5. LONGITUDINAL TENSILE PROPERTIES OF COLD-WORKED 18Ni (250) MARAGING STEEL(5)

Reduction During Cold Working, per cent	Aging Temperature, F	Aging Time, hours	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation, per cent	Reduction in Area, per cent
20	850	1	246	244	4.9	46
20	850	1	247	247	4.5	41
20	900	1	263	263	4.3	52
20	900	1	263	263	3.6	52
20	850	3	268	268	4.6	45
20	850	3	259	257	4.3	50
20	900	3	275	273	4.3	56
20	900	3	284	282	4.8	52
20	850	10	292	289	4.6	49
20	850	10	292	287	4.9	55
20	900	10	288	283	3.5	47
20	900	10	280	274	4.8	48
30	850	1	278	277	3.7	50
30	850	1	277	277	4.5	53
30	900	1	291	291	4.3	54
30	900	1	293	291	4.4	47
30	850	3	297	295	4.2	37
30	850	3	289	288	4.2	53
30	900	3	294	290	4.0	49
30	900	3	300	297	4.7	54
30	850	10	306	302	4.1	42
30	850	10	306	299	4.4	47
30	900	10	294	289	5.0	49
30	900	10	293	290	4.9	54
70	850	1	293	290	2.5	43
70	850	1	294	294	4.3	47
70	900	1	308	306	4.0	49
70	900	1	284	284	1.9	47
70	850	3	295	295	4.2	47
70	850	3	309	302	4.2	49
70	900	3	307	303	3.3	47
70	900	3	317	315	4.4	57
70	850	10	319	319	3.0	48
70	850	10	327	326	3.4	43
70	900	10	305	300	4.1	51
70	900	10	307	297	4.5	53

TABLE A-6. TRANSVERSE TENSILE PROPERTIES OF COLD-WORKED 18Ni (250) MARAGING STEEL[5]

Reduction During Cold Working, per cent	Aging Temperature, F	Aging Time, hours	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation, per cent	Reduction in Area, per cent
20	850	1	264	262	4.4	54
20	850	1	259	257	4.7	51
20	900	1	285	285	3.2	46
20	900	1	274	274	3.1	45
20	850	3	289	289	2.8	49
20	850	3	285	281	4.5	48
20	900	3	291	287	4.1	47
20	850	10	301	297	4.2	41
20	850	10	305	304	2.8	43
20	900	10	301	295	4.5	42
20	900	10	303	302	3.9	41
30	850	1	283	282	4.2	44
30	850	1	291	289	3.4	45
30	900	1	306	301	4.0	44
30	900	1	306	302	3.2	49
30	850	3	272	272	1.2	41
30	850	3	302	301	3.8	39
30	900	3	317	310	4.1	42
30	900	3	305	302	4.1	43
30	850	10	324	319	3.8	44
30	850	10	321	316	3.8	42
30	900	10	316	308	3.8	47
30	900	10	315	306	4.0	44
40	850	1	294	294	4.0	35
40	850	1	286	283	3.7	43
40	900	1	306	301	3.6	43
40	900	1	304	302	3.4	44
40	850	3	303	303	3.8	44
40	850	3	310	306	4.0	42
40	900	3	316	311	2.6	39
40	900	3	313	311	3.3	40
40	850	10	327	320	3.8	38
40	850	10	329	324	3.8	36
40	900	10	315	308	4.3	38
40	900	10	314	309	4.0	41

TABLE A-6. (Continued)

Reduction During Cold Working, per cent	Aging Temperature, F	Aging Time, hours	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation, per cent	Reduction in Area, per cent
50	850	3	Failed at Pinhole			--
50	850	3	322	318	3.9	37
50	900	3	331	327	3.3	38
50	900	3	327	324	4.0	45
50	850	10	Failed at Pinhole			--
50	850	10	Failed at Pinhole			--
50	900	10	323	318	3.6	35
50	900	10	323	318	2.7	39
70	850	1	301	301	2.4	37
70	850	1	309	309	1.3	23
70	900	1	322	322	2.5	17
70	900	1	320	318	2.5	18
70	850	3	Failed at Pinhole			--
70	850	3	Failed at Pinhole			--
70	900	3	323	320	2.0	6
70	900	3	327	325	2.0	12
70	850	10	Failed at Pinhole			--
70	850	10	Failed at Pinhole			--
70	900	10	326	314	3.1	18
70	900	10	317	315	2.2	18

TABLE A-7. LONGITUDINAL TENSILE PROPERTIES OF COLD-WORKED 18Ni (300) MARAGING STEEL(5)

Reduction During Cold Working, per cent	Aging Temperature, F	Aging Time, hours	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation, per cent	Reduction in Area, per cent
20	850	1	275	268	5.4	32
20	850	1	286	285	5	42
20	900	1	309	307	4.8	47
20	900	1	316	316	4.3	49
20	850	3	284	284	4.5	49
20	850	3	290	286	4.4	44
20	900	3	313	311	4.6	49
20	900	3	323	320	4.0	49
20	850	10	331	330	4.2	48
20	850	10	330	326	4.3	47
20	900	10	327	326	3.7	50
20	900	10	325	324	4.8	49
30	850	1	294	283	4.5	47
30	850	1	299	299	4.	20
30	900	1	317	315	4.7	52
30	900	1	324	324	3.7	49
30	850	3	309	308	4.5	48
30	850	3	306	306	4.0	49
30	900	3	330	329	4.5	49
30	900	3	326	325	1.7	46
30	850	10	333	332	4.0	48
30	850	10	333	331	4.4	42
30	900	10	332	329	4.3	49
30	900	10	332	327	4.2	51
40	850	1	302	294	3.7	37
40	850	1	315	311	4	46
40	900	1	335	334	2.1	48
40	900	1	328	326	4.5	51
40	850	3	316	316	4.5	49
40	850	3	317	315	4.0	45
40	900	3	317	317	3.9	47
40	900	3	338	333	4.5	49
40	850	10	338	333	4.2	51
40	850	10	342	342	3.9	46
40	900	10	342	340	4.0	47
40	900	10	338	333	3.7	43

TABLE A-7. (Continued)

Reduction During Cold Working, per cent	Aging Temperature, F	Aging Time, hours	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation, per cent	Reduction in Area, per cent
50	850	1	330	328	3	23
50	850	1	328	327	3	44
50	900	1		Failed at Pinhole		
50	900	1		Failed at Pinhole		
50	850	3		Failed at Pinhole		
50	850	3	327	327	3.7	46
50	900	3		Failed at Pinhole		
50	900	3		Failed at Pinhole		
50	850	10	338	333	4.2	51
50	850	10		Failed at Pinhole		
50	900	10	347	346	4.4	46
50	900	10		Failed at Pinhole		
70	850	1	317	308	3.9	30
70	850	1	310	308	4	36
70	900	1	328	325	4.0	41
70	900	1	324	323	4.1	45
70	850	3	316	313	4.0	40
70	850	3	313	313	3.4	25
70	900	3	344	342	4.5	42
70	900	3	334	332	4.0	46
70	850	10	336	334	3.1	34
70	850	10	337	336	4.2	33
70	900	10	337	333	4.0	44
70	900	10		Failed at Pinhole		

TABLE A-8. TRANSVERSE TENSILE PROPERTIES OF COLD-WORKED 18Ni (300) MARAGING STEEL[5]

Reduction During Cold Working, per cent	Aging Temperature, F	Aging Time, hours	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation, per cent	Reduction in Area, per cent
20	850	1	301	298	2.1	31
20	850	1	313	310	1.8	40
20	900	1	323	317	4.3	38
20	900	1	342	342	2.5	41
20	850	3	317	313	3.8	36
20	850	3	313	305	3.0	41
20	900	3	332	329	2.8	40
20	900	3	351	349	4.2	37
20	850	10	343	340	4.0	36
20	850	10	348	346	3.8	36
20	900	10	354	351	2.6	15
20	900	10	340	337	3.5	40
40	850	1	312	309	3.2	12
40	850	1	325	322	2.6	24
40	900	1	Failed at Pinhole LE			
40	900	1	346	344	2.8	29
40	850	3	327	325	3.0	29
40	850	3	334	330	3.5	29
40	900	3	275	Failed at Pinhole		
40	900	3	341	Failed at Pinhole		
40	850	10	248	Failed at Pinhole		
40	850	10	304	Failed at Pinhole		
40	900	10	328	Failed at Pinhole		
40	900	10	315	Failed at Pinhole		
50	850	1	316	Failed at Pinhole		
50	850	1	--	Failed at Pinhole		
50	900	1	--	Failed at Pinhole		
50	900	1	--	Failed at Pinhole		
50	850	3	--	Failed at Pinhole		
50	850	3	--	Failed at Pinhole		
50	900	3	--	Failed at Pinhole		
50	900	3	--	Failed at Pinhole		
50	850	10	--	Failed at Pinhole		
50	850	10	--	Failed at Pinhole		

TABLE A-9. TENSILE PROPERTIES OF 18Ni(200) MARAGING STEEL SHEET

Specimens Annealed at 1500 F, Air Cooled, and Aged at 900 F for 3 or 4 Hours

Thickness, inch	Direction	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent	Heat	Reference
			Vacuum-Arc Remelt				
0.070	T	229	220	5	--	3950933[a]	26
0.125	T	222	216	6	--	3950933[a]	26
0.125	T	222	215	6	--	3960524[b]	26
0.125	T	222	210	7	--	3960523[c]	26
0.187	T	223	221	11	43	07427[d]	11
0.187	T	217	206	11	39	07427[d]	11

	Heat	Ni	Co	Mo	Ti
(a)	3950933	18.9	9.0	3.5	0.22
(b)	3960524	19.0	9.0	3.5	0.22
(c)	3960523	17.8	8.5	3.5	0.23
(d)	07427	18.67	8.76	3.4	0.15 (data are for front and back ends of coil)

TABLE A-10. TENSILE PROPERTIES OF 18Ni(200) MARAGING STEEL PLATE

Specimens Annealed at 1500 F, Air Cooled, and Aged at 900 F for 3 or 4 Hours

Thickness, inch	Direction	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent	Heat	Reference
			Air Melt				
0.5	L	246	241	12.5	56	(a)	39
0.5	T	252	245	9.5	46	(a)	39
0.5	L	230	223	7.5	55	84625(b)	25
0.5	T	236	232	6.2	46	84625(b)	25
1	L	242	234	10.5	56	(a)	39
1	T	242	235	9.5	46	(a)	39
1	L	236	226	9.8	47	(c)	20
1	T	234	226	7.5	40	(c)	20
			Vacuum-Arc Remelt				
0.375	T	223	219	16	48	07427(d)	28
0.375	T	227	224	16	43	07427(d)	28
0.375	T	224	222	10	59	3960526(e)	26
0.75	L	224	215	12	62	3950933(f)	26
0.75	T	225	217	10	47	3950933(f)	26
1	L	214	208	23 (in 0.5")	56	(g)	48
1	T	213	211	11.5	58	07427(d)	28
1	T	204	200	12.5	61	07427(d)	28
1.25	T	233	228	10	51	3960524(h)	26
1.375	T	232	225	9	46	3960523(i)	26
1.75	L	230	225	11	60	3950933(f)	26
1.75	T	229	223	8	45	3950933(f)	26

	Heat	Ni	Co	Mo	Ti
(a)	-- (10T.)	18.6	7.0	4.5	0.22
(b)	84625	18.6	7.0	4.5	0.22
(c)	-- (10T.)	18.6	6.9	4.6	0.22
(d)	07427 (15T.)	18.67	8.76	3.4	0.15
(e)	3960526	17.8	8.5	3.5	0.22
(f)	3950933	18.9	9.0	3.5	0.22
(g)	--	18.06	8.5	3.1	0.17
(h)	3960524	19.0	9.0	3.5	0.22
(i)	3960523	17.8	8.5	3.5	0.23

Specimens from Heat 07427 are from front and back ends of plate.

TABLE A-11. TENSILE PROPERTIES OF HEAVY SECTIONS OF 18Ni (200) MARAGING STEEL

Specimens Annealed at 1500 F, Air Cooled, and Aged at 900 F for 3 or 4 Hours

Size and Shape of Section	Direction	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent	Heat	Reference
			Air Arc Melt				
1/2" bar	L	243	238	12	55	(a)	39
Bar	L	241	238	12	58	(a)	39
			Vacuum-Arc Remelt				
4" x 4"	T	230	222	7	35	3950933[b]	26
7" x 7"	T	219	209	8	38	3950933[b]	26
4" x 16"	T	228	217	8	40	3960524[c]	26
4" x 16"	T	215	205	9	46	3960523[d]	26
4" x 16"	T	210	200	10	50	3960526[e]	26

	Heat	Ni	Co	Mo	Ti	Size of Heat
(a)	--	18.6	7.0	4.5	0.22	10 tons
(b)	3950933	18.9	9.0	3.5	0.22	--
(c)	3960524	19.0	9.0	3.5	0.22	--
(d)	3960523	17.8	8.5	3.5	0.23	--
(e)	3960526	17.8	8.5	3.5	0.22	--

TABLE A-12. TENSILE PROPERTIES OF 18Ni(250) MARAGING STEEL SHEET

Specimens Annealed at 1500 F, Air Cooled, and Aged at 900 F for 3 or 4 Hours

Thickness, inch	Direction	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent	Heat	Reference
			Air Melt				
0.025	L	257	252	3.0	23	--	49
0.025	T	260	254	3.0	23	--	49
0.043	L	265	256	6.0	38	--	49
0.043	T	268	260	5.5	34	--	49
0.074	L	259	253	8.0	48	--	49
0.074	T	263	256	8.0	44	--	49
0.135	L	272	268	10	51	--	49
0.135	T	280	274	10	49	--	49
0.195	T	272	266	4.5	41	A6939(a)	5
0.195	T	281	276	6.0	39	A7035(b)	5
			Vacuum-Arc Remelt				
0.025	L	246	232	--	--	(c)	50
0.025	T	252	243	2.5	--	(c)	50
0.040	T	256	246	3.0	--	3930575(d)	26
0.050	T	286	284	4.7	--	23832(e)	19
0.063	L	271	269	3.4(in 2")	--	23832(e)	51
0.063	T	281	276	3.3(in 2")	--	23832(e)	51
0.064	L	254	246	7.3	--	(c)	50
0.064	T	254	247	5.0	--	(c)	50
0.064	--	262	252	4.5	--	(f)	39
0.067	--	279	274	3.0	--	23664(g)	5
0.075	L	234	230	7.8(in 2")	--	24285(h)	15
0.075	T	242	233	7.5(in 2")	--	24285(h)	15
0.080	L	254	245	5.0	--	3930575(d)	26
0.080	T	256	243	5.0	--	3930575(d)	26
0.090	--	239	232	11	51	Heat B(i)	27
0.100	T	264	258	4.0	--	3930553(j)	26
0.125	L	274	270	5.2(in 2")	--	07249(k)	52
0.125	T	287	284	5.2(in 2")	--	07249(k)	52
0.130	T	278	257	5.0	--	16815(l)	11
0.187	T	284	282	6.0	26	07328 front (m)	28
0.187	T	273	272	7.5	29	07328 back (m)	28
0.200	T	268	262	6.5	--	3930553(j)	26
0.220	T	258	255	7.0	--	3930575	26

Footnotes appear on following page.

Footnotes for Table A-12:

	Heat	Ni	Co	Mo	Ti
(a)	A6939 (1/2T.)	18.2	7.4	4.7	0.35
(b)	A7035 (1/2T.)	18.7	7.5	4.8	0.50
(c)	--	18.57	8.38	4.98	0.43
(d)	3930575	18.55	7.95	4.72	0.41
(e)	23832	18.60	7.74	5.04	0.42
(f)	--	18.75	7.5	4.85	0.43
(g)	23664	18.2	8.0	4.8	0.37
(h)	24285	--	--	--	--
(i)	Heat B	18.96	7.34	5.04	0.29
(j)	3930553	18.4	7.82	4.82	0.36
(k)	07249	18.51	7.73	4.90	0.40
(l)	16715	18.45	7.55	4.65	0.51
(m)	07328 (15T.)	18.87	7.89	4.90	0.31

TABLE A-13. TENSILE PROPERTIES OF 18Ni(250) MARAGING STEEL PLATE

Specimens Annealed at 1500 F, Air Cooled, and Aged at 900 F for 3 or 4 Hours

Thickness, inch	Direction	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent	Heat	Reference
			Air Melt				
0.4375	L	275	265	10	46	--	53
0.4375	T	269	265	10	53	--	
0.50	L	255	248	20	40	X-13371[a]	16
0.50	T	250	240	21	41	X-13371[a]	16
0.50	L	281	275	7.9	44	13371[b]	4
0.50	T	268	259	8.8	47	13371[b]	4
0.75	L	262	256	10	48	(c)	1
0.75	T	269	264	9	45	(c)	1
0.75	L	259	253	11 (in 2")	45	Heat A[d]	54
0.75	T	260	254	9 (in 2")	36	Heat A[d]	54
			Vacuum Degassed				
0.307	L	274	266	9	43	120E290VM[e]	55
0.307	T	278	270	7.5	37	120E290VM[e]	
0.400	L	278	273	9	47	120G097VM[f]	55
0.400	T	295	290	8	41	120G097VM[f]	
0.500	L	270	261	10	44	120D163VM[g]	55
0.500	T	278	268	9	43	120D163VM[g]	55
0.50	L	257	249	9	46	(h)	1
0.50	T	269	260	9	44	(h)	1
0.560	L	255	247	11	54	120G298VM[i]	55
0.560	T	261	252	9	45	120G298VM[i]	
0.740	L	277	275	8	40	120G097VM[f]	55
0.740	T	281	276	9	39	120G097VM[f]	
2.50	T	252	244	10	39	120G298VM[i]	55
			Vacuum-Arc Remelt				
0.290	T	263	252	8	--	3930553[j]	26
0.375	T	275	272	6	32	07328 front[k]	28
0.375	T	282	276	6	32	07328 back[k]	28
0.375	T	255	246	11	55	3930575[l]	26
0.375	L	263	257	10.0	--	(m)	56
0.375	T	266	256	10.5	--	(m)	56
0.50	T	260	252	10	46	3930575[l]	26
0.50	L	260	248	10.5	50	(915 F age)[n]	48
0.50	L	288	278	9.7	42	3888472[o]	
0.50	T	283	274	9.0	40	3888472[o]	
0.50	L	287	277	8.2	39	3888473[p]	
0.50	T	293	282	8.8	39	3888473[p]	

TABLE A-13. (Continued)

Thickness, inch	Direction	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent	Heat	Reference
			Vacuum-Arc Remelt (Continued)				
0.50	L	230	223	7.5 (in 1.4")	55	84625[q]	25
0.50	T	236	232	6.3 (in 1.4")	46	84625[q]	25
0.50	--	270	261	13	56	Heat A[r]	27
0.50	--	230	223	12	55	Heat G[s]	27
0.625	T	261	252	10	56	3930553[j]	26
1	T	253	251	8.5	59	07328 front[k]	28
1	T	254	252	9.5	46	07328 back[k]	

Heat	Ni	Co	Mo	Ti
(a) X 13371	17.83	7.41	4.70	0.46
(b) 13371	18.65	8.05	4.90	0.52
(c) -- (20 T.)	18.2	7.9	4.6	0.46
(d) Heat A	17.73	7.40	4.80	0.39
(e) 120E290VM (7 T.)	18.98	8.05	4.90	0.59
(f) 120G097VM (7 T.)	18.12	7.88	4.77	0.49
(g) 120D163VM (7 T.)	18.04	8.10	4.70	0.50
(h) -- (7 T.)	18.0	8.1	4.7	0.50
(i) 120G298VM (7 T.)	18.25	7.40	4.85	0.17
(j) 3930553	18.4	7.82	4.82	0.36
(k) 07328 (15 T.)	18.87	7.89	4.90	0.31
(l) 3930575	18.55	7.95	4.72	0.41
(m) --	18.35	7.80	4.70	0.33
(n) --	18.30	7.83	4.82	0.35
(o) 3888472	18.60	9.10	5.10	0.62
(p) 3888473	18.80	8.82	4.85	0.65
(q) 84625	18.6	7.0	4.5	0.22
(r) Heat A	18.47	7.54	4.90	0.48
(s) Heat G	18.96	8.43	4.77	0.30

Note: Specimens from Heats 13371, 3888472, and 3888473 were aged at 900 F for 4 hours.

TABLE A-14. TENSILE PROPERTIES OF HEAVY SECTIONS OF 18Ni (250) MARAGING STEEL

Specimens Annealed at 1500 F, Air Cooled, and Aged at 900 F for 3 or 4 Hours

Size and Shape	Direction	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent	Heat	Reference
				Air Melt			
1/2" bar	L	256	247	--	64	--	57
1-3/4" bar	L	267	259	11	58	Induction melt[a]	1
4" x 16" x 36"	L	248	241	10	47	3930575[b]	1
4" x 16" x 36"	T	250	242	8.5	40	3930575[b]	1
4" x 16" x 36"	ST	241	234	7	30	3930575[b]	1
6" dia. forging	L	253	244	--	52	--	57
9" dia. forging	T	248	238	--	--	(c)	57
9" dia. forging	T	240	232	--	45	--	57
12" dia. forging	T	247	239	--	43	--	57
14" x 17" billet	L	273	256	4	21	Induction melt[d]	1
14" x 17" billet	T	275	258	4	18	Ditto	1
14" x 17" billet	ST	274	257	5	18	"	1
10.5" x 10.5" billet	T	281	264	8	26	Induction melt[d]	1
10.5" x 10.5" billet	ST	277	260	3	25	Ditto	1
				Vacuum-Arc Remelt			
5/8" bar	L	264	256	12	58	A6824[e]	5
5/8" bar	L	263	250	14	59	23832[f]	40
3/4" bar	L	269	265	11 (in 1.5")	53	06759[g]	23
3/4" bar	L	248	234	14	59	Heat C[h]	27
1" bar	L	263	256	11 (in 2")	49	06759[g]	15
1" bar	L	263	254	9	42	--	--
1" square	T	274	270	10	54	--	--
1-1/2" RCS	L	264	255	11	62	06137[i]	5
2-1/2" square	L	272	266	10	52	3960502[j]	26
1-1/2" x 5"	L	278	268	9	48	3960502[j]	26
1-1/2" x 5"	T	275	266	8	40	3960502[j]	26
3-1/2" RCS	T	263	253	4.6 (in 1.5")	21	A7225[k]	23
4" square	L	273	265	8.5	40	3960502[j]	26
4" square	T	267	258	6.0	29	3960502[j]	26
4" RCS	T	266	249	3.5	12	(16" dia. ingot)	--

TABLE A-14. (Continued)

Size and Shape	Direction	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent	Heat	Reference
			Vacuum-Arc Remelt (Continued)				
5" square	L	260	250	10	52	3930553[l]	26
5" square	T	259	248	7.5	36	3930553[l]	26
5-1/2" square	T (MR)	270	265	7	33	1015[m]	17
5-1/2" square	T (C)	270	265	6	34	1015[m]	17
5-3/4" square	L	265	256	12	58	(17" dia. ingot)[n]	1
5-3/4" square	T	270	256	10	46	(17" dia. ingot)[n]	1
6" RCS	T	272	260	3.5	12	(16" dia. ingot)	--
6" square	T (MR)	267	263	5.5	23	1013[o]	17
6" square	T (C)	264	261	5.0	28	1013[o]	17
6" square	T (bot. MR)	250	245	9.0	52	1016[p]	17
6" square	T (bot. C)	247	243	9.5	47	1016[p]	17
6" square	T (top-MR)	248	244	8.7	40	1016[p]	17
6" square	T (top-C)	246	241	9.5	48	1016[p]	17
7" RCS	T	266	249	3.5	12	--	--
7" square	L	258	242	7.0	32	Same heat	--
7" square	T	257	243	4.5	16		--
9" square	T (bot. MR)	253	248	8.5	41	1017[q]	17
9" square	T (bot. C)	252	248	8.0	36	1017[q]	17
9" square	T (top-MR)	246	242	8.0	40	1017[q]	17
9" square	T (top-C)	250	246	8.0	40	1017[q]	17
10" RCS	T	271	263	10	44	40059[r]	5
11" dia. x 7"	T	256	242	3	10	--	--

	Heat	Ni	Co	Mo	Ti
(a)	-- (1/2 T.)	18.45	7.48	4.8	0.48
(b)	3930575 (15 T.)	18.55	7.95	4.73	0.41
(c)	--	17.6	7.3	4.8	0.50
(d)	-- (2.5 T.)	18.32	9.16	5.36	0.52
(e)	A6824 (1/2 T.)	18.54	7.38	5.34	0.44
(f)	23832	18.34	7.69	5.2	0.45
(g)	06759	18.20	7.22	4.78	0.50
(h)	Heat C	18.45	7.46	5.0	0.51
(i)	06137 (1/2 T.)	18.2	7.6	4.8	0.42
(j)	3960502	18.47	6.95	4.83	0.51
(k)	A7225	18.89	7.64	4.96	0.41
(l)	3930553	18.4	7.82	4.82	0.36
(m)	1015	18.84	8.23	5.07	0.39
(n)	-- (2.5 T.)	18.34	7.69	5.2	0.45
(o)	1013	18.86	8.27	5.0	0.41
(p)	1016	18.69	7.86	5.0	0.31
(q)	1017	18.52	7.84	4.82	0.39
(r)	40059 (2 T.)	19.1	8.2	4.4	0.40

Note: MR = mid-radius
C = center.

TABLE A-15. TENSILE PROPERTIES OF 18Ni (300) MARAGING STEEL SHEET

Specimens Annealed at 1500 F, Air Cooled, and Aged at 900 F for 3 or 4 Hours

Thickness, inch	Direction	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent	Heat	Reference
			Air Melt				
0.050	--	296	282	4	--	X-1603[a]	50
			Vacuum-Arc Remelt				
0.025	L	267	248	--	--	(b)	50
0.025	T	283	272	2	--	(b)	50
0.063	L	284	280	3.0 (in 2")	-- --	23831[c]	51
0.063	T	294	290	2.5 (in 2")	--	23831[c]	51
0.064	L	279	271	6	--	(b)	50
0.064	T	286	278	5	--	(b)	50
0.065	L	264	251	7.0 (in 2")	--	06498[d]	15
0.065	T	268	257	6.8 (in 2")	--	06498[d]	15
0.075	L	274	266	7.2 (in 2")	--	W-24178[e]	15
0.075	T	278	271	6.8 (in 2")	--	W-24178[e]	15
0.100	L	301	296	4.8 (in 2")	--	--[f]	31
0.125	L	288	285	4.0 (in 2")	--	07146[g]	52
0.125	T	302	298	3.3 (in 2")	--	07146[g]	52
0.130	--	269	266	1.0	50	Heat E[h]	27
0.140	--	304	294	5.8 (in 2")	--	(i)	44
0.140	--	300	294	4.8 (in 2")	--	(j)	44
0.195	--	314	308	5	32	06269[k]	5
0.200	L	304	299	9.0 (in 2")	--	(f)	31
0.200	T	301	307	7.8 (in 2")	--	(f)	31
0.25	--	322	317	5.2	30	(l)	1
0.25	--	296	284	6.4 (in 2")	--	(m)	44

Footnotes appear on following page.

Footnotes for Table A-15:

	Heat	Ni	Co	Mo	Ti
(a)	X-1603	18.4	8.8	5.00	0.78
(b)	--	18.72	9.08	4.88	0.73
(c)	23831	18.61	9.05	5.00	0.71
(d)	06498	--	--	--	--
(e)	W-24178	--	--	--	--
(f)	--	18.57	8.92	4.95	0.76
(g)	07146	18.66	9.09	4.85	0.56
(h)	Heat E	18.96	9.13	4.76	0.43
(i)	--	18.63	9.00	4.66	0.66
(j)	--	17.80	8.96	4.85	0.63
(k)	06269 (1/2 T.)	18.3	9.0	4.8	0.65
(l)	-- (1/2 T.)	18.27	9.03	4.8	0.65
(m)	--	18.43	8.71	4.06	0.70

TABLE A-16. TENSILE PROPERTIES OF 18Ni (300) MARAGING STEEL PLATE

Specimens Annealed at 1500 F, Air Cooled, and Aged at 900 F for 3 or 4 Hours

Thickness, inch	Direction	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent	Heat	Reference
			Vacuum-Arc Remelt				
0.360	L	292	289	20	45	23831[a]	47
0.360	T	297	292	18	48	23831[a]	47
0.375	L	305	297	7.1	--	(b)	56
0.375	T	306	299	6.5	--	(b)	56
0.5	--	290	274	10	48	Heat F[c]	27
0.5	L	301	292	7.5	40	07148[d]	4
0.5	T	301	292	7.2	37	07148[d]	4

	Heat	Ni	Co	Mo	Ti
(a)	23831	18.61	9.05	5.00	0.71
(b)	--	18.32	9.06	4.88	0.73
(c)	Heat F	18.32	9.06	4.88	0.73
(d)	07148	18.7	9.30	5.12	0.65

TABLE A-17. TENSILE PROPERTIES OF HEAVY SECTIONS OF 18Ni (300) MARAGING STEEL

Specimens Annealed at 1500 F, Air Cooled, and Aged at 900 F for 3 or 4 Hours

Size and Shape	Direction	Tensile Strength, 1000 psi	Yield Strength 0.2% Offset, 1000 psi	Elongation in 1 Inch, per cent	Reduction in Area, per cent	Heat	Reference
			Air Melt				
5/8" bar	L	284	277	--	61	(a)	58
			Vacuum-Arc Remelt				
5/8" bar	L	289	277	10	48	23831(b)	40
3/4" bar	L	293	286	11 (in 1.5")	52	06461(c)	23
3/4" bar	L	295	293	11	57	(d)	1
4" square	--	297	290	7.0	37	(d)	1
4" square	L	307	300	5.6	28	07148(e)	4
4" square	T	305	295	3.9	18	07148(e)	4
4" square	ST	307	300	3.5	17	07148(e)	4
4" square	T (MR)	288	283	4.0	19	2037(f)	17
4" square	T (C)	289	[illegible]	4.5	24	2037(f)	17
4" square	T (MR)	279	2[illegible]	7.0	37	2043(g)	
4" square	T (C)	282	272	7.0	32	2043(g)	17
4" square	T (MR)	290	287	6.5	32	2036(h)	17
4" square	T (C)	290	286	5.5	22	2036(h)	17
4-1/2" square	T (MR)	275	270	7.5	37	2046(i)	17
4-1/2" square	T (C)	272	267	8.5	43	2046(i)	17
3-1/2" x 7" bar	L	282	272	9.5	24	06989(j)	
3-1/2" x 7" bar	ST	275	261	3.5	8.5	06989(j)	18
3-1/2" x 7" bar	L	282	271	7.5	26	07081(k)	18
3-1/2" x 7" bar	ST	276	264	2.5	6.0	07081(k)	18
5" square	T (top MR)	287	283	7.7	35	2047(l)	17
5" square	T (top C)	282	279	8.5	42	2047(l)	17
5" square	T (bot. MR)	282	277	8.5	35	2047(l)	17
5" square	T (bot. C)	283	279	7.5	34	2047(l)	17
6" square	T (MR)	282	278	9.0	42	2046(i)	17
	T (C)	282	278	9.5	47	2046(i)	17
6-1/4" square	T (top MR)	276	2[illegible]2	8.7	47	2048(m)	17
6-1/4" square	T (top C)	276	270	8.7	44	2048(m)	17
6-1/4" square	T (bot. MR)	278	273	8.7	46	2048(m)	17
6-1/4" square	T (bot. C)	278	272	9.5	44	2048(m)	17
18-1/2" x 2-1/2"	T	297	282	7	26	--(n)	1
18-1/2" x 2-1/2"	ST	292	273	9	26	--(n)	1

Footnotes appear on following page.

Footnotes for Table A-17:

	Heat	Ni	Co	Mo	Ti
(a)	--	18.5	9.8	4.8	0.6
(b)	23831	18.2	9.05	4.84	0.69
(c)	06461	18.77	8.98	4.88	0.77
(d)	-- (2-1/2 T.)	18.7	8.75	4.9	0.83
(e)	07148	18.7	9.30	5.12	0.65
(f)	2037	18.79	9.38	4.90	0.58
(g)	2043	18.40	8.98	4.98	0.60
(h)	2036	18.80	9.30	4.96	0.57
(i)	2046	18.52	9.00	4.86	0.60
(j)	06989	18.62	8.74	4.75	0.63
(k)	07081	18.61	9.14	4.72	0.58
(l)	2047	18.53	9.06	4.95	0.65
(m)	2048	18.47	9.00	4.91	0.58
(n)	-- (2-1/2 T.)	18.32	9.06	4.88	0.73

Note: Specimens from Heat 07148 aged at 900 F for 4 hours.
MR = mid-radius
C = center.

TABLE A-18. TABULATION OF MINIMUM, MAXIMUM, AND AVERAGE ROOM-TEMPERATURE TENSILE PROPERTIES OF THREE GRADES OF 18 PER CENT NICKEL MARAGING STEELS BY FORM, MELTING PRACTICE, AND TESTING DIRECTION

All Specimens Annealed at 1500 F, Air Cooled, and Aged at 900 F for 3 or 4 Hours

Form	Melting Practice	Test Direction	Tensile Strength, 1000 psi Min	Tensile Strength, 1000 psi Max	Tensile Strength, 1000 psi Over-All Average	Yield Strength, 1000 psi Min	Yield Strength, 1000 psi Max	Yield Strength, 1000 psi Over-All Average	Elongation, per cent Min	Elongation, per cent Max	Elongation, per cent Over-All Average	Number of Values[a], N
					(200) Grade							
Sheet	VAR	T	217	229	223	206	221	215	5	11	7.5	6
Plate	AM	L	230	246	239	223	241	231	7.5	12.5	10	4
Plate	AM	T	234	252	241	226	245	235	6	9.5	8	4
Plate	VAR	L	214	230	223	208	225	216	11	12	11.5	3
Plate	VAR	T	204	233	223	200	228	219	8	16	11.5	9
Heavy sections	AM	L	241	243	242	238	238	238	12	12	12	2
Heavy sections	VAR	T	210	230	220	200	222	211	7	10	8.5	5
					(250) Grade							
Sheet	AM	L	257	272	263	252	268	258	3	10	7	4
Sheet	AM	T	260	281	271	254	276	264	3	10	6	6
Sheet	VAR	L	234	279	257	230	274	250	3	11	6	9
Sheet	VAR	T	242	287	266	233	284	260	2.5	7.5	5	14
Plate	AM	L	255	281	266	248	275	259	8	20	12	5
Plate	AM	T	250	239	263	240	265	256	9	21	11.5	5
Plate	VD	L	255	278	269	247	275	262	8	11	9.5	6
Plate	VD	T	252	295	273	244	290	266	7.5	10	7.5	7
Plate	VAR	L	230	288	261	223	278	252	7.5	13	10.5	7
Plate	VAR	T	236	293	265	232	282	258	6	11	8.5	12
Heavy sections	AM	L	248	273	259	241	259	249	4	11	8.5	5
Heavy sections	AM	T	240	275	257	232	264	246	4	8.5	7	6
Heavy sections	AM	ST	241	277	264	234	260	250	3	7	5	3
Heavy sections	VAR	L	248	278	265	234	268	255	7	14	10.5	13
Heavy sections	VAR	T	246	275	261	241	270	252	5	10	7	24
					(300) Grade							
Sheet	AM	L	--	--	296	--	--	282	--	--	4	1
Sheet	VAR	L	264	322	290	248	317	283	1	9	3	14
Sheet	VAR	T	268	302	287	257	307	282	2	8	5	7
Plate	VAR	L	290	304	297	272	297	288	7	20	11	4
Plate	VAR	T	297	306	301	292	299	294	6.5	18	10.5	3
Heavy sections	AM	L	--	--	284	--	--	277	--	--	--	1
Heavy sections	VAR	L	282	307	292	271	300	284	5.5	11	9.0	7
Heavy sections	VAR	T	272	305	284	267	295	278	4	9.5	7.5	20
Heavy sections	VAR	ST	275	307	288	261	300	275	2.5	9	4.5	4

(a) These values are from Tables A-9 through A-17.

TABLE A-19. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 18 PER CENT NICKEL MARAGING STEEL SHEET

Thickness, inch	Direction	Test Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Tensile Strength, per cent of RT strength	Yield Strength, per cent of RT yield	Heat	Reference
				(250) Grade					
--	L	RT	262	252	4.5	100	100	--	59
		-320	329	315	4.5	125	125		
--	--	RT	262	252	4.5	100	100	--	39
		-320	320	307	4.0	122	122		
--	L	RT	273	267	--	100	100	--	53
		-320	333	322	--	122	120.5		
--	L	RT	267	262	4.2	100	100	--	53
		-320	337	323	3.0	126	123		
	T	RT	278	274	3.0	100	100		
		-320	348	336	1.5	125	123		
0.036	T	RT	250	219	5 (in 1")	100	100	2E-3756[a]	60
		300	231	197	3	92.5	90		
		600	214	175	3	85.5	80		
0.050	T	RT	257	235	4 (in 1")	100	100	24285[b]	60
		300	236	218	4	92	92.8		
		600	222	170	4	86.5	72.4		
0.063	L	RT	271	269	3.4 (in 2")	100	100	23832[c]	51
		-100	290	288	3.0	107	107		
		600	234	227	3.2	86.5	84.4		
		900	193	183	6.0	71.2	68		
0.075	L	RT	237	230	7.8 (in 2")	100	100	24285[b]	15
		-100	253	248	6.8	107	108		
		-45	250	240	8.0	105.5	104.2		
		40	239	227	8.0	101	98.7		
		200	228	221	8.2	96.3	96		
		300	221	212	7.8	93.3	92.2		
0.125	L	RT	274	270	5.2 (in 2")	100	100	07249[d]	23
	L	300	255	253	5.0	93	93.8		
	T	RT	287	284	5.2	100	100		
	T	300	267	261	5.2	93	92		

TABLE A-19. (Continued)

Thickness, inch	Direction	Test Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Tensile Strength, per cent of RT strength	Yield Strength, per cent of RT yield	Heat	Reference
				(300) Grade					
--	L	RT	299	293	--	100	100	--	53
		-320	362	352	--	121	120		
	T	RT	306	301	--	100	100		
		-320	374	362	--	122	120		
0.063	L	RT	284	280	3.0 (in 2")	100	100	23831(e)	51
		-100	305	302	3.0	107	108		
		600	249	242	2.7	87.7	86.5		
		900	213	201	7.0	75	71.8		
0.065	L	RT	264	251	7.0 (in 2")	100	100	06498(f)	15
		-100	286	276	6.2	108	110		
		-45	278	266	6.2	105.2	106		
		40	266	253	7.0	100.7	100.8		
		200	253	243	6.2	96	97		
		300	249	237	6.5	94.4	94.5		
0.075	L	RT	274	266	7.2 (in 2")	100	100	W-24178(g)	15
		-100	294	287	7.2	107	108		
		-45	285	277	7.5	104	104		
		40	274	265	6.8	100	99.6		
		200	261	253	6.8	95.2	95		
		300	255	244	6.5	93	91.8		
0.100	L	79	284	280	--	100	100	Heat E(h)	12
	T	79	286	283	--	100	100		
	T	-96	310	301	--	108.3	106.3		
	T	-65	306	300	--	107	106		
	T	-20	300	291	--	105	103		
	T	154	278	272	--	97.2	96.2		
0.125	L	RT	288	285	4.0 (in 2")	100	100	07146(i)	23
	L	300	273	268	4.5	94.8	94		
	T	RT	302	298	3.3	100	100		
	T	300	280	273	3.9	92.7	91.5		

Heat Treatment: Annealed at 1500 F, air cooled, and aged at 1500 F for 3 or 4 hours.

Heat	Ni	Co	Mo	Ti
(a) 2E-3756 (AM)	18.40	7.76	4.78	0.36
(b) 24285 (VAR)	18.32	7.45	4.82	0.39
(c) 23832 (VAR)	18.60	7.74	5.04	0.42
(d) 07249 (VAR)	18.51	7.73	4.90	0.40
(e) 23831 (VAR)	18.61	9.05	5.00	0.71
(f) 06498 (VAR)				
(g) W-24178 (VAR)				
(h) Heat E	18.7	10.03	5.00	0.76
(i) 07146 (VAR)	18.66	9.09	4.85	0.56

TABLE A-20. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF PLATE AND BAR STOCK OF 18 PER CENT NICKEL MARAGING STEELS

Size and Form	Direction	Test Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent	Tensile Strength, per cent of RT strength	Yield Strength, per cent of RT yield	Heat	Reference
					(250) Grade					
Plate	L	RT	244	233	12	57	100	100	--	59
	L	-320	305	291	9	40	125	125		
	T	RT	243	232	10	44	100	100		
	T	-320	310	292	7.3	29	127.5	126		
Bar	L	RT	263	254	11	56	100	100	--	53
		600	244	234	11.5	56	93	92.2		
		700	235	224	12	56	89.3	88.2		
		800	227	211	13.5	58	86.5	83.0		
		900	207	192	16.5	65	78.8	75.7		
		950	191	177	21	71	72.7	69.7		
		1000	166	150	23	73	63.2	59		
Bar	L	RT	260	251	11	56	100	100	--	53
		600	226	212	11	56	87	84.5		
		700	223	206	12	56	85.8	82.2		
		800	210	192	13.5	56	80.8	76.5		
		900	197	175	14.5	62	75.8	69.7		
		950	182	164	16	66	70	65.4		
		1000	156	140	20	73	60	55.8		
5/8" bar	L	RT	262	250	13.5	58.5	100	100	23832[a]	40
		300	238	222	--	--	91	89		
		600	222	210	--	--	84.8	84		
		800	209	188	--	--	79.8	75.2		
		1000	184	162	--	--	70.3	65		
3/4" bar	L	RT	269	265	10.9	52.8	100	100	06759[b]	23
		-100	289	280	10.7	52.0	107.3	105.6		
		600	233	221	10.9	52.7	86.8	83.4		
		900	200	184	15.9	60.5	74.5	69.5		

TABLE A-20. (Continued)

Size and Form	Direction	Test Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent	Tensile Strength, per cent of RT strength	Yield Strength, per cent of RT yield	Heat	Reference
				(250) Grade (Continued)						
1" bar	L	RT	263	256	11.0	49.2	100	100	06759(b)	15
		-100	281	274	9.5	44.8	107	107		
		-45	271	262	10.8	46.4	103	102.3		
		40	264	258	11.0	48.8	100.3	100.7		
		200	255	247	11.2	50.4	97	96.5		
		300	245	237	11.5	50.8	93.2	92.7		
				(300) Grade						
Bar	L	RT	295	293	11	57	100	100	--	1
		300	272	267	10	58	92.2	91.2		
		500	263	254	10	56	89.2	86.8		
		600	257	247	10	56	87.2	84.3		
		700	250	237	9	54	84.8	81.0		
		800	241	230	12	57	81.9	78.5		
		900	214	199	15	37	72.5	68.0		
		1000	180	168	23	79	61.0	57.3		
Bar	L	RT	288	282	12.5	62	100	100	--	53
		600	250	240	12.0	62	86.8	85.2		
		700	246	236	12.5	62	85.5	83.7		
		800	240	223	14.0	61	83.3	79.0		
		900	216	203	17.3	68	75.0	72.0		
		950	196	181	22.0	76	68.0	64.2		
		1000	165	155	24.0	77	57.3	55.0		
5/8" bar	L	RT	289	277	10.0	48	100	100	23831(c)	40
		300	266	246	--	--	92.0	88.8		
		600	247	236	--	--	85.5	85.2		
		800	235	222	--	--	81.3	80.2		
		900	210	198	--	--	72.7	71.5		
		1000	206	192	--	--	71.4	69.3		

TABLE A-20. (Continued)

Size and Form	Direction	Test Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent	Tensile Strength, per cent of RT strength	Yield Strength, per cent of RT yield	Heat	Reference
				(300) Grade (Continued)						
3/4" bar	L	RT	293	286	11.2	52.5	100	100	06461[d]	23
		-100	314	306	10.7	51.2	107	107		
		600	245	230	10.9	51.0	83.7	80.5		
		900	217	200	16.2	58.8	74.0	70.0		
3/4" bar	L	70	300	281	6	23	100	100	32[e]	22
		300	272	251	8	32	90.7	89.3		
		500	259	235	9	40	86.5	83.7		
		800	241	218	10	41	80.3	77.6		
		900	231	205	12	49	77.0	73.0		
		1000	203	186	16	60	67.7	66.2		
3.5" x 7" bar	L	RT	281	272	--	--	100	100	06989[f]	21
		350	258	229	--	--	92.0	84.2		
		650	236	219	--	--	84.0	80.5		
		700	239	218	--	--	85.0	80.2		
		900	226	204	--	--	80.5	75.0		
3.5" x 7" bar	L	RT	282	272	--	--	100	100	07081[g]	21
		350	259	229	--	--	92.0	84.2		
		650	243	228	--	--	86.2	83.8		
		700	241	226	--	--	85.5	83.2		
		800	233	214	--	--	82.6	78.8		

Heat treatment: Annealed at 1500 F, air cooled, and aged at 900 F for 3 or 4 hours except as noted.

	Heat	Ni	Co	Mo	Ti
(a)	23832 (VAR)	18.34	7.69	5.2	0.45
(b)	06759 (VAR)	18.20	7.22	4.78	0.50
(c)	23831 (VAR)	18.61	9.05	5.00	0.71
(d)	06461 (VAR)	18.77	8.98	4.83	0.77
(e)	Lab induction melt	15.2	9.2	5.1	0.70 (1800 F, air cool, 900 F 3 hr)
(f)	06989 (VAR)	18.62	8.74	4.75	0.63
(g)	07081 (VAR)	18.61	9.14	4.72	0.58

VAR – Vacuum-arc remelt.

TABLE A-21. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF CAST 18 PER CENT NICKEL MARAGING STEEL

Test Temperature, F	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent	Tensile Strength, per cent of RT strength	Yield Strength, per cent of RT yield	Heat	Reference
RT	270	254	6.5	21.9	100	100	06990-1	6
600	225	201	10.0	38.0	83.3	79.0		
800	214	193	8.5	30.2	79.2	76.0		
1000	164	157	13.0	47.2	60.8	61.8		

Composition: 0.03C, 0.14Si, <0.10Mn, <0.01S, <0.01P, 4.74Mo, 18.32Ni, 9.33Co, 0.45Ti, 0.12Al, 0.0035B, <0.[illegible]1Zr.

Heat Treatment: Annealed 2100 F 4 hours, air cooled, maraged 900 F 3 hours, and air cooled.

Original master heat was vacuum-consumable-electrode melted and cast into small ingots for remelting and casting as blanks for the test specimens.

TABLE A-22. EFFECT OF TEMPERATURE ON THE ELASTIC MODULUS OF THE 18 PER CENT NICKEL MARAGING STEELS

Specimens Annealed at 1500 F, Air Cooled, and Aged at 900 F for 3 or 4 Hours

Size and Shape	Grade	Temperature, F	Direction	Elastic Modulus, psi x 10^6	Heat	Reference
0.125" sheet	250	RT	L	26.6	07249[a]	52
		300	L	26.0		
		RT	T	27.4		
		300	T	26.5		
Plate	250	RT	L	26.5	--	20
		RT	T	26.5		
Bar	250	RT	L	26.5	--	53
		600	L	22.1		
		800	L	22.0		
		900	L	19.0		
		1000	L	18.7		
Bar	250	RT	L	26.5	--	53
		600	L	22.3		
		800	L	22.0		
		900	L	20.1		
		950	L	19.3		
		1000	L	19.1		
0.125" sheet	300	RT	L	27.2	07146[b]	52
		300	L	25.9		
		RT	T	28.0		
		300	T	27.5		
0.140" sheet	300	RT	--	26.8	Heat 1[c]	44
0.140" sheet	300	RT	--	26.6	Heat 2[d]	44
0.250" plate	300	RT	--	26.4	Heat A[e]	44
Bar	300	RT	L	27.5	--	53
		600	L	22.9		
		800	L	22.1		
		900	L	20.1		
		1000	L	19.4		
3-1/2" x 7" bar	300	RT	L	26.5	--	18
		650	L	24.0		
		RT	L (comp.)	28.3		
		650	L (comp.)	25.7		

	Heat	Ni	Co	Mo	Ti
(a)	07249 (VAR)	18.51	7.73	4.90	0.40
(b)	07146 (VAR)	18.66	9.09	4.85	0.56
(c)	Heat 1 (VAR)	18.63	9.00	4.66	0.66
(d)	Heat 2 (VAR)	17.80	8.96	4.85	0.63
(e)	Heat A (VAR)	18.43	8.71	4.06	0.70

TABLE A-23. EFFECT OF TEMPERATURE ON THE COMPRESSIVE,

Size and Shape	Grade	Temperature, F	Direction	Compressive Yield Strength, 1000 psi	Compressive Yield, per cent of RT Yield	Shear Strength, 1000 psi	Shear Strength, per cent of RT Strength
Sheet	250	RT	--	247	--	143	--
Sheet	300	RT	T	296	--		
Plate	250	RT	L	247	--	143	--
			T	248	--	143	--
Bar	300	RT	L	287	100	163	100
		350	L	258	90		
		650	L	241	84	133	81.5
		800	L	230	80.2	124	76
Bar	300	RT	L	289	100	163	100
		350	L	262	90.6		
		650	L	244	84.5	139	85.2
		800	L	232	80.3	125	76.7

Heat	Ni	Co	Mo	Ti
(a) 06989(VAR)	18.62	8.74	4.75	0.63
(b) 07081(VAR)	18.61	9.14	4.72	0.58

Heat treatment: Annealed at 1500 F, air cooled, and aged at 900 F for 3 or 4 hours.

SHEAR, AND BEARING PROPERTIES OF THE 18 PER CENT NICKEL MARAGING STEELS

Bearing (e/D = 1.5)				Bearing (e/D = 2.0)					
Bearing Ultimate Strength, 1000 psi	Strength, per cent of RT Strength	Bearing Yield Strength, 1000 psi	Yield, per cent of RT Yield	Bearing Ultimate Strength, 1000 psi	Strength, per cent of RT Strength	Bearing Yield Strength, 1000 psi	Yield, per cent of RT Yield	Heat	Reference
									1
								23832	19
									20
391	100	382	100	500	100	474	100	06989[a]	
339	86.7	331	86.7	436	87.2	401	84.7		
326	83.4	319	83.5	421	84.2	395	83.4		
402	100	372	100	513	100	431	100	07081[b]	21
344	85.5	330	88.6	449	87.5	391	90.8		
328	81.5	318	85.5	440	85.8	384	89		

TABLE A-24. EFFECT OF ELEVATED-TEMPERATURE EXPOSURE ON THE ROOM-TEMPERATURE TENSILE PROPERTIES OF 18 PER CENT NICKEL MARAGING STEELS

Size and Shape	Grade	Exposure Temperature, F	Exposure Time, hours	Direction	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation, per cent	Reduction in Area, per cent	Heat	Reference
0.025" sheet	250	None	--	T	230	228	1.5	--	23560[b]	13
		600	250	T	238	237	1.2	--		
		600[a]	250	T	255	--	1.2	--		
0.050" sheet	250	300	5	T	267	256	3.5	--	3960502[c]	60
		300	50	T	268	259	3.5	--		
		400	5	T	269	260	3.0	--		
		400	50	T	267	259	3.5	--		
		500	5	T	268	260	2.5	--		
		500	50	T	267	259	3.0	--		
		600	5	T	269	261	3.0	--		
		600	50	T	271	263	3.0	--		
		700	5	T	273	263	2.5	--		
		700	50	T	281	274	3.0	--		
0.035" sheet	300	None	--	T	288	283	2.5	--	H-23847[d]	13
		600	250	T	289	284	2.0	--		
		600[a]	250	T	297	293	1.5	--		
3.5" x 7" bar	300	None	--	L	282	272	8.5	24.8	07081[e]	18
		650	500	L	293	287	5.6	22.2		
		650	1000	L	297	291	4.8	16.6		
		800	500	L	309	298	3.6	13.8		
		800	1000	L	307	302	3.6	9.8		

(a) Specimens stressed at 150,000 psi during exposure.

Heat	Ni	Co	Mo	Ti	Heat Treatment
(b) 26560(VAR)	18.72	7.87	4.59	0.24	Aged at 900 F for 3 hours before exposure
(c) 3960502(AM)	18.48	7.00	4.84	0.50	Aged at 900 F for 4 hours before exposure
(d) H-23847(VAR)	18.32	9.06	4.88	0.73	Aged at 900 F for 3 hours before exposure
(e) 07081(VAR)	18.61	9.14	4.72	0.58	Aged at 900 F for 3 hours before exposure

There was no effect of exposure at 500 F for 1000 hours for Heat 07081.

TABLE A-25. CHARPY IMPACT PROPERTIES OF 18 PER CENT NICKEL MARAGING STEEL PLATE

Standard V-Notch Charpy Specimens Annealed at 1500 F, Air Cooled, and Aged at 900 F for 3 Hours

Plate Thickness, in.	Direction	Test Temperature, F	Impact Energy, ft-lb	Heat	Reference
		18Ni (200) Grade			
0.400	L	RT	28	23560[a]	16
0.5	L	RT	26	W24059[b]	24
	L	212	26		
	L	40	25		
	L	0	25		
	L	-40	23		
	L	-100	21		
	L	-320	18		
	T	RT	19		
	T	212	20		
	T	40	18		
	T	0	18		
	T	-40	16		
	T	-100	14		
	T	-320	12		
		18Ni (250) Grade			
0.5	L	RT	24		59
	L	0	24		
	L	-100	21		
	L	-175	21		
	L	-244	20		
	L	-320	20		
	T	RT	18		
0.5	T	RT	18	84625[c]	25
	T	750	20		
	T	500	19		
	T	250	19		
	T	-40	18		
	T	-180	16		
	T	-320	13		
0.5	L	RT	23	(Air melt)	1
	L	0	23		
	L	-100	21		
	L	-175	21		
	L	-244	20		
	L	-320	20		
	L	-420	16		

TABLE A-25. (Continued)

Plate Thickness, in.	Direction	Test Temperature, F	Impact Energy, ft-lb	Heat	Reference
		18Ni (250) Grade (Continued)			
0.5	L	-40	14.7	Heat A(d)	27
0.5	L	RT	13-24	120D163VM(e)	55
	T	RT	13-19		
	T	300	17		
	T	200	17		
	T	150	14		
	T	125	14		
	T	75	16		
	T	0	16		
	T	-40	16		
	T	-65	18		
	T	-100	17		
	T	-150	14		
	T	-200	14		
	T	-320	12		
	L*	RT	17-19		
	T*	RT	13-18		
0.560	L	RT	21-24	120G298VM(f)	55
	T	RT	16-18		
0.625	L(A)	RT	24	3930553(g)	26
	L(A)	-40	22		
	L(A)	-100	24		
	L(A)	-320	17		
	L(B)	RT	31		
	L(B)	-40	27		
	L(B)	-100	26		
	L(B)	-320	21		
0.625	-	RT	17	3930502(h)	26
		-40	17		
		-100	14		
		-320	12		
0.740	L	RT	12-14	120G097VM(i)	55
	T	RT	11-13		
1.625	L + T	RT	14.5-16.5	X14637(j)	47
		18Ni (300) Grade			
0.5	L	-40	14.9	Heat F(k)	27

Footnotes appear on following page.

Footnotes for Table A-25:

Heat	Ni	Co	Mo	Ti
(a) 23560 (VAR)	18.72	7.87	4.59	0.24
(b) W24059	18.19	8.53	3.36	0.08
(c) 84625 (VAR)	18.9	8.43	4.77	0.30
(d) Heat A	18.47	7.54	4.90	0.48
(e) 120D163VM (VAR)	18.04	8.10	4.70	0.50
(f) 120G298VM (VAR)	18.25	7.40	4.85	0.17
(g) 3930553 (VAR)	18.40	7.82	4.82	0.36
(h) 3930502 (VAR)	18.47	6.95	4.83	0.51
(i) 120G097VM (VAR)	18.12	7.88	4.77	0.49
(j) X14637	Not reported			Aged 915 F 4 hours
(k) Heat F (VAR)	18.32	9.06	4.88	0.73

VAR – Vacuum-arc remelted; AM – air melt.
(A) From top of ingot; (B) from bottom of ingot.
*As rolled and aged at 900 F for 3 hours.

TABLE A-26. CHARPY IMPACT PROPERTIES OF 18 PER CENT NICKEL MARAGING STEELS AS BARS, FORGINGS, AND BILLETS

Standard V-Notch Charpy Specimens Annealed at 1500 F, Air Cooled and Aged at 900 F for 3 Hours Except as Noted

Size and Shape	Direction	Test Temperature, F	Impact Energy, ft-lb	Heat	Reference
		18Ni (250) Grade			
1/2" sq bar	L	RT	20	(Air Melted)	1
	L	1100	56		
	L	900	34		
	L	600	34		
	L	300	35		
	L	-40	19		
	L	-65	19		
	L	-100	18		
	L	-320	13		
5/8" dia. bar	L	RT	28	23832(a)	40
	L	-100	27		
	L	-320	14		
3/4" dia. bar	L	RT	30	Heat C(b)	27
3/4" dia. bar	L	RT	16	06759(c)	23
	L	-100	17		
1.5" x 5" forging	L	RT	12	3930502(d)	26
		-40	12		
		-100	10		
		-320	8		
5" sq billet	L(A)	RT	28	(VAR)	26
	L(A)	-40	28		
	L(A)	-100	27		
	L(A)	-320	20		
	L(B)	RT	28		
	L(B)	-40	27		
	L(B)	-320	19		
		18Ni (300) Grade			
1/2" sq bar	L	RT	17	(VAR)	1
	L	1100	44		
	L	900	24		
	L	600	28		
	L	300	30		
	L	-40	17		
	L	-65	16		
	L	-100	15		

TABLE A-26 (Continued)

Size and Shape	Direction	Test Temperature, F	Impact Energy, ft-lb	Heat	Reference
		18Ni (300) Grade (Continued)			
1/2" sq bar	L	-320	11		
Bar	L*	RT	22-25		59
	L*	-320	12-14		
5/8" dia. bar	L	RT	28	23831(e)	40
	L	-100	27		
	L	-320	15		
3/4" dia. bar	L	RT	19	06461(f)	23
	L	-100	21		
Dome forging	Tangential	70	11	C-40148(g)	14
	Radial	70	13		
	Tangential	-100	9		

Heat	Ni	Co	Mo	Ti
(a) 23832 (VAR)	18.34	7.69	5.20	0.45
(b) Heat C	18.45	7.46	5.0	0.51
(c) 06759 (VAR)	18.20	7.22	4.78	0.50
(d) 3930502	18.47	6.95	4.83	0.51
(e) 23831 (VAR)	18.20	9.05	4.84	0.69
(f) 06461 (VAR)	18.77	8.98	4.88	0.77
(g) C-40148	19.08	8.59	4.80	0.60

VAR - vacuum-arc remelted.

(A) From top of ingot; (B) from bottom of ingot.

*Hot rolled and aged at 900 F.

TABLE A-27. CHARPY IMPACT PROPERTIES OF CAST 18 NICKEL MARAGING STEELS

Specimens – Standard V-Notch Charpy

Grade	Casting Thickness, inches	Melting Practice[a]	Heat Treatment	Test Temp, F	Impact Energy, ft-lb	Heat	Reference
220	1	AM	1800 F 4 hr, 900 F 3 hr	-40	14	62-029[b]	61
			2000 F 4 hr, 900 F 3 hr	-40	17		
			2200 F 4 hr, 900 F 3 hr	-40	18		
250	1	VD	2100 F 4 hr, 900 F 3 hr	70	16	62-214[c]	61
				-40	13		
230	1	VD	2100 F 4 hr, 900 F 3 hr	70	13	62-393[d]	61
				-40	12		
240	1	VD	2000 F 4 hr, AC, 900 F 3 hr	70	12	62-282[e]	61
				-40	10		
250	1	AM	2100 F 4 hr, AC, 900 F 3 hr	70	17	62-227[f]	61
				-40	17		
230	2			70	10	62-393	61
				-40	8		
250	2			70	16	62-227	61
				-40	14		
230	3			70	10	62-393	61
				-40	8		
250	3			70	16	62-227	61
				-40	10		
240	1-in. keel block	IM argon atmos.	2100 F 4 hr, 900 F 3 hr	RT	17	39[g]	62

(a) AM – air melted; VD – vacuum degassed; IM – induction melted.

	Heat	Ni	Co	Mo	Ti
(b)	62-029	16.60	10.35	4.60	0.27
(c)	62-214	16.89	10.30	4.75	0.36
(d)	62-393	17.15	10.40	4.77	0.33
(e)	62-282	17.18	10.40	4.62	0.41
(f)	62-227	17.21	10.47	4.72	0.37
(g)	39	16.92	10.40	4.72	0.38

TABLE A-28. RESULTS OF PRECRACKED CHARPY IMPACT TESTS ON 18 PER CENT NICKEL MARAGING STEEL PLATE

Precracked V-Notch Charpy Specimens

Plate Thickness, in.	Aging Treatment	Direction	Test Temperature, F	Impact Energy, W/A-in.-lb/in.^{2}	Heat	Reference
			18Ni (200) Grade			
1/2	875F 18hr	L	RT	1130	28889[a]	4
			18Ni (250) Grade			
1/2	900 F 4 hr	L	RT	336	120D163[b]	4
		L	400	584		
		L	200	460		
		L	0	303		
		L	-100	90		
		T	RT	353		
		T	400	514		
		T	200	401		
		T	0	238		
		T	-100	123		
1/2	875 F 8 hr	L	RT	353	120D298[c]	4
		T	RT	442		
1/2	875 F 8 hr	L	RT	228	120G097[d]	4
		T	RT	212		

	Heat	Ni	Co	Mo	Ti
(a)	28889 (VD)	18.00	8.51	3.30	0.19
(b)	120D163 (VD)	18.60	8.00	4.95	0.48
(c)	120D298		Not reported		
(d)	120G097 (VD)	18.12	7.88	4.77	0.49

TABLE A-29. TENSILE DATA FROM EDGE-NOTCHED SHEET SPECIMENS OF 18 PER CENT NICKEL MARAGING STEELS

Data are for Edge-Notched Specimens With Notch Root Radii of 0.001 Inch or Less

Thickness, in.	Preliminary Treatments	Specimen Width, in.	Test Temperature, F	Direction	Notched Strength, 1000 psi	NS/YS Ratio	NS/TS Ratio	Heat	Reference
			18Ni (250) Grade						
0.025	1500 F, AC, 900 F 3 hr	1	RT	T	209	0.92	0.91	23560[a]	13
	1500 F, AC, 900 F 3 hr	1	-65	T	215	0.99	0.97		
	1500 F, AC, 900 F 3 hr	1	600	T	170	0.91	0.88		
	900 F 3 hr + 600 F 250 hr	1	RT	T	206	0.915	0.89		
0.028	900 F 4 hr	1	RT	T	195	--	0.78	2E-3756[b]	60
0.036	900 F 3 hr	1	70	T	219	--	0.875	2E-3756[b]	60
		1	300	T	197	--	0.85		
		1	600	T	175	--	0.82		
0.050	900 F 4 hr	1	RT	T	235	0.91	0.89	3960502[c]	60
0.050	900 F 3 hr	1	70	T	235	--	0.915	24285[d]	60
		1	300	T	218	--	0.925		
		1	600	T	170	--	0.77		
0.050	1500 F, AC, 900 F 3 hr (K_t = 15)		RT	T	251	0.87	0.86	23832[e]	19
0.063	1500 F, AC, 900 F 3 hr (K_t > 15)		RT	L	226	0.84	0.835	23832[e]	51
			RT	T	193	0.70	0.69		
			-150	L	229	--	--		
			-150	T	200	--	--		
0.125	As rolled + 900 F 3 hr (K_t > 16)		RT	L	155	0.575	0.565	07249[f]	52
			RT	T	177	0.625	0.62		
			300	L	174	0.69	0.68		
			300	T	154	0.59	0.58		
--	20% CW + 900 F 3 hr	2	RT	L	236	0.85	--	--	5
		2	RT	T	167	0.58	--		
	30% CW + 900 F 3 hr	2	RT	L	210	0.71	--		
		2	RT	T	139	0.46	--		
	40% CW + 900 F 3 hr	2	RT	L	212	0.72	--		
		2	RT	T	114	0.37	--		
	50% CW + 900 F 3 hr	2	RT	L	188	0.60	--		
		2	RT	T	98	0.30	--		
	70% CW + 900 F 3 hr	2	RT	L	157	0.51	--		
			RT	T	104	0.32	--		
			18Ni (300) Grade						
0.035	1500 F, AC, 900 F 3 hr	1	RT	T	210	0.74	0.73	H-23847[g]	13
	1500 F, AC, 900 F 3 hr	1	-65	T	202	0.715	0.70		
	1500 F, AC, 900 F 3 hr	1	600	T	169	0.69	0.66		
	900 F 3 hr, 600 F 250 hr	1	RT	T	207	0.73	0.72		

TABLE A-29. (Continued)

Thickness, in.	Preliminary Treatments	Specimen Width, in.	Test Temperature, F	Direction	Notched Strength, 1000 psi	NS/YS Ratio	NS/TS Ratio	Heat	Reference
			18Ni (300) Grade (Continued)						
0.063	1500 F, AC, 900 F 3 hr	(K_t > 15)	RT	L	214	0.765	0.755	23831[h]	51
			RT	T	178	0.615	0.605		
			-100	L	204	0.68	0.67		
			-100	T	176	--	--		
0.100	1500 F, AC, 900 F 3 hr	1	RT	L	276	0.99	0.98	Heat E[i]	12
		1	RT	T	230	0.815	0.805		
		1	-96	T	243	0.80	0.785		
		1	-65	T	214	0.715	0.70		
		1	-20	T	236	0.81	0.79		
		1	154	T	236	0.87	0.85		
0.115	900 F 3 hr	2	RT	--	217	0.82	0.80	7C056[j]	5
	1500 F, AC, 900 F 3 hr	2	RT	--	209	0.79	0.78		
	30% CW + 900 F 3 hr	2	RT	--	215	0.75	0.74		
	50% CW + 900 F 3 hr	2	RT	--	166	0.55	0.55		
0.115	900 F 3 hr	2	RT	--	162	0.53	0.52	7C057[k]	5
	1500 F, AC, 900 F 3 hr	2	RT	--	138	0.45	0.44		
	30% CW, 900 F 3 hr	2	RT	--	132	0.41	0.40		
	50% CW, 900 F 3 hr	2	RT	--	133	0.39	0.39		
0.125	As rolled + 900 F 3 hr	(K_t > 16)	RT	L	137	0.48	0.475	07146[l]	52
			RT	T	114	0.38	0.38		
			300	L	129	0.48	0.475		
			300	T	125	0.46	0.445		
--	20% CW + 900 F 3 hr	2	RT	L	204	0.65	--	--	5
	30% CW + 900 F 3 hr	2	RT	L	190	0.58	--		
		2	RT	T	106	0.32	--		
	40% CW + 900 F 3 hr	2	RT	L	141	0.43	--		
		2	RT	T	95	0.28	--		
	50% CW + 900 F 3 hr	2	RT	L	114	0.32	--		
		2	RT	T	81	0.23	--		
	70% CW + 900 F 3 hr	2	RT	L	132	0.39	--		
		2	RT	T	80	0.23	--		

	Heat	Ni	Co	Mo	Ti
(a)	23560 (VAR)	18.72	7.87	4.59	0.24
(b)	2E-3756 (AM)	18.40	7.76	4.78	0.36
(c)	3960502 (AM)	18.48	7.00	4.84	0.50
(d)	24285 (VAR)	18.32	7.45	4.82	0.39
(e)	23832 (VAR)	18.6	7.74	5.04	0.42
(f)	07249 (VAR)	18.51	7.73	4.90	0.40
(g)	H-23847 (VAR)	18.32	9.06	4.88	0.73
(h)	23831 (VAR)	18.61	9.05	5.00	0.71
(i)	Heat E	18.7	10.03	5.00	0.76
(j)	7C056	On low side of composition range.			
(k)	7C057	On high side of composition range.			
(l)	07146 (VAR)	18.66	9.09	4.85	0.56

TABLE A-30. TENSILE DATA FROM CENTER-NOTCHED SHEET SPECIMENS OF 18 PER CENT NICKEL MARAGING STEELS

Thickness, in.	Specimen Width, in.	Test Temperature, F	Direction	Notched Strength, 1000 psi	NS/YS Ratio	NS/TS Ratio	Heat	Reference
				18Ni (250) Grade				
0.075	1.75	RT	L	209	0.91	0.88	24285[a]	15
		RT	T	184	0.79	0.76		
		-100	L	218	0.88	0.86		
		-45	L	214	0.85	0.815		
		40	L	206	0.905	0.86		
		200	L	200	0.905	0.88		
		300	L	184	0.87	0.835		
0.080	--	RT	T(A)	250	0.98	0.96	3930553[b]	26
		RT	T(B)	266	1.02	1.00		
0.125	3.0	RT	L	160	0.59	0.585	07249[c]	52
		RT	T	153	0.54	0.53		
		300	L	155	0.615	0.61		
		300	T	146	0.56	0.545		
0.177	--	RT	L(A)	255	--	--	3930553[b]	26
0.175		RT	T(A)	248	0.95	0.93		
0.176		RT	L(B)	276	--	--		
0.177		RT	T(B)	253	0.97	0.94		
0.180	--	RT	T	274	1.08	1.06	3930575[d]	26
				18Ni (300) Grade				
0.065	1.75	RT	L	185	0.735	0.70	06498[e]	15
		RT	T	186	0.725	0.695		
		-100	L	192	0.695	0.67		
		-45	L	195	0.73	0.70		
		40	L	192	0.76	0.72		
		200	L	182	0.75	0.72		
		300	L	178	0.75	0.715		
0.075	1.75	RT	L	178	0.665	0.65	W-24178[f]	15
		RT	T	165	0.61	0.59		
		-100	L	178	0.62	0.605		
		-45	L	177	0.64	0.62		
		40	L	166	0.625	0.605		
		200	L	172	0.68	0.66		
		300	L	172	0.71	0.675		
0.125	3	RT	L	142	0.50	0.495	07146[g]	52
		RT	T	121	0.405	0.40		
		300	L	138	0.515	0.505		
		300	T	119	0.435	0.425		
0.140	2.25	RT	--	193	0.655	0.635	Heat 1[h]	44
0.140	2.25	RT	--	145	0.495	0.485	Heat 2[i]	44
0.180	3	-65	ST	70	0.26	0.25	(From 4" x 12" billet)	37

Footnotes appear on following page.

Footnotes for Table A-30:

Heat	Ni	Co	Mo	Ti	
(a) 24285 (VAR)	18.32	7.45	4.82	0.39	
(b) 3930553 (VAR)	18.40	7.82	4.82	0.36	
(c) 07249 (VAR)	18.51	7.73	4.90	0.40	As-rolled + 900 F 3 hr
(d) 3930575 (VAR)	18.55	7.95	4.72	0.41	
(e) 06498 (VAR)	18.36	9.10	4.93	0.60	
(f) W-24178 (VAR)	18.69	8.90	4.92	0.62	
(g) 07146 (VAR)	18.66	9.09	4.85	0.56	As-rolled + 900 F 3 hr
(h) Heat 1 (VAR)	18.63	9.00	4.66	0.66	
(i) Heat 2 (VAR)	17.80	8.96	4.85	0.63	

Data are for center-notched specimens with fatigue cracks at the ends of the notches. All specimens annealed at 1500 F, air cooled, and aged at 900 F 3 hours except as noted.

VAR - Vacuum-arc remelted; ST - short transverse direction.
(A) From top of ingot; (B) from bottom of ingot.

TABLE A-31. TENSILE DATA FROM PART-THROUGH FATIGUE-CRACKED SPECIMENS OF SHEET AND PLATE OF 18 PER CENT NICKEL MARAGING STEELS

Thickness, in.	Specimen Width, in.	Fatigue Crack Length, in.	Fatigue Crack Depth, in.	Fatigue Crack Area, sq in.	Specimen Direction	Notched Strength, 1000 psi	NS/YS Ratio	NS/TS Ratio	Heat	Reference
					18Ni (200) Grade					
0.109	1.5	0.22	(2[illegible].2%)	--	L	210	--	--	A7499(b)	47
		0.29	(32.1%)	--	L	206	--	--		
		0.34	(43.1%)	--	L	199	--	--		
					18Ni (250) Grade					
0.106	1.5	0.29	(22.6%)	--	T	241	--	--	A7352(c)	47
		0.34	(37.7%)	--	T	230	--	--		
		0.22	(25.5%)	--	L	242	--	--		
		0.[illegible]	(33.6%)	--	L	237	--	--		
		0.35	(43.9%)	--	L	230	--	--		
0.107	1.5	0.28	(29.9%)	--	T	259	1.01	0.98	X14359(d)	47
		0.33	(33.0%)	--	T	265	1.03	1.00		
		0.30	(31.7%)	--	L	270	1.07	1.04		
		0.34	(37.4%)	--	L	255	1.01	0.99		
					18Ni (300) Grade					
0.100(a)	1.0	0.046	0.015	0.0005	L	309	1.04	1.03	40196(e)	31
		0.053	0.015	0.0006	L	309	1.04	1.03		
		0.087	0.025	0.0017	L	307	1.03	1.02		
		0.093	0.028	0.0021	L	306	1.03	1.02		
		0.155	0.039	0.0047	L	257	0.87	0.85		
		0.201	0.050	0.0078	L	242	0.82	0.81		
		0.193	0.050	0.0076	L	249	0.84	0.83		
0.200(a)	1.0	0.104	0.040	0.0033	L	304	1.02	1.00	40196(e)	31
		0.096	0.040	0.0030	L	308	1.03	1.02		
		0.142	0.052	0.0058	L	291	0.97	0.96		
		0.201	0.067	0.0106	L	222	0.74	0.73		
		0.196	0.064	0.0098	L	251	0.84	0.83		
		0.106	0.039	0.0031	T	308	1.00	0.99		
		0.101	0.043	0.0034	T	310	1.01	1.00		
		0.155	0.054	0.0066	T	263	0.86	0.85		
		0.154	0.052	0.0063	T	273	0.89	0.88		
		0.200	0.061	0.0096	T	223	0.73	0.72		
		0.205	0.069	0.0109	T	217	0.71	0.70		
0.140	1.0	0.121	0.029	0.004	--	311	1.06	1.02	Heat 1(f)	44
		0.204	0.042	0.007	--	312	1.06	1.02		
		0.221	0.068	0.012	--	302	1.03	0.99		
		0.278	0.072	0.016	--	307	1.04	1.01		
		0.269	0.076	0.016	--	312	1.06	1.02		
		0.371	0.089	0.026	--	292	0.99	0.96		
0.140	1.0	0.119	0.033	0.003	--	296	1.01	0.99	Heat 2(g)	44
		0.184	0.043	0.006	--	292	0.99	0.97		
		0.225	0.061	0.011	--	239	0.81	0.80		
		0.255	0.067	0.013	--	247	0.84	0.82		
		0.293	0.068	0.016	--	228	0.78	0.76		
		0.224	0.066	0.012	--	272	0.92	0.91		

TABLE A-31. (Continued)

Thickness, in.	Specimen Width, in.	Fatigue Crack Length, in.	Fatigue Crack Depth, in.	Fatigue Crack Area, sq in.	Specimen Direction	Notched Strength, 1000 psi	NS/YS Ratio	NS/TS Ratio	Heat	Reference
				18Ni (300) Grade (Continued)						
0.250	1.0	0.110	0.035	0.003	--	303	1.07	1.02	Heat A(h)	44
		0.151	0.058	0.007	--	296	1.04	1.00		
		0.225	0.088	0.016	--	307	1.08	1.04		
		0.276	0.098	0.021	--	271	0.95	0.92		
		0.320	0.112	0.028	--	256	0.90	0.86		

(a) From 3/8-inch-thick plate

	Heat	Ni	Co	Mo	Ti
(b)	A7499(VAR)	18.70	8.59	3.29	0.19
(c)	A7352(VAR)	18.43	7.63	4.85	0.39
(d)	X14359	17.73	7.40	4.80	0.39
(e)	40196(VAR)	18.57	8.92	4.95	0.76
(f)	Heat 1(VAR)	18.63	9.00	4.66	0.66
(g)	Heat 2(VAR)	17.80	8.96	4.85	0.63
(h)	Heat A(VAR)	18.43	8.71	4.06	0.70

All specimens annealed at 1500 F, air cooled, and aged at 900 F for 3 hours. Room-temperature tests on individual specimens. VAR – vacuum-arc remelted.

TABLE A-32. TENSILE DATA FROM ROUND NOTCHED SPECIMENS FROM BAR, PLATE, AND FORGINGS OF 18 PER CENT NICKEL MARAGING STEELS

Specimens Annealed at 1500 F, Air Cooled, and Aged at 900 F for 3 Hours

Form and Size	Notch	Test Temperature, F	Direction	Notched Strength, 1000 psi	NS/YS Ratio	NS/TS Ratio	Heat	Reference
			18Ni (200) Grade					
Plate, 0.400"	Dia. = 0.225", 0.001" = r.r.	RT	--	238	--	--	23560(f)	16
			18Ni (250) Grade					
Plate, 0.5"	K_t = 6.3	RT	L	338	1.51	1.47	84625(g)	25
		RT	T	332	1.43	1.40		
Bar, 0.5" dia.	0.001" = r.r.(a)	RT	L	386	1.56	1.50	Code A	57
Bar 0.625" dia.	K_t = 9.5	RT	L	372	1.49	1.42	23832(h)	40
Bar 0.75" dia.	K_t = 6.25	RT	L	378	1.43	1.40	06759(i)	23
		-100	L	386	1.38	1.33		
		600	L	330	1.49	1.42		
		900	L	298	1.62	1.49		
Bar, 1" dia.	Fatigue cracked(b)	RT	L	202	0.79	0.765	06759(i)	15
		-100	L	151	0.55	0.54		
		-45	L	111	0.425	0.41		
		40	L	132	0.51	0.50		
		200	L	202	0.82	0.795		
		300	L	314	1.32	1.28		
Forging, 6" dia.	K_t = 10	RT	L	331	1.27	1.22	--	57
		RT	T	302	1.16	1.13	--	
Forging, 6" dia.	0.001" r.r.(c)	RT	--	337	1.38	1.33	Code B	
Forging, 9" dia.	0.001" r.r.(c)	RT	T	206	0.86	0.83	Code C(j)	
Forging, 9" dia.	0.001" r.r.(c)	RT	T	335	1.40	1.36	Code D	
Forging, 12" dia.	0.001" r.r.(c)	RT	T	306	1.32	1.28	Code D	
			18Ni (300) Grade					
Bar, 0.625" dia.	0.0031" r.r.(d)	RT	L	431	1.56	1.52	Code E	58
Bar, 0.625" dia.	K_t = 9.5	RT	L	354	1.28	1.22	23831(k)	40

TABLE A-32. (Continued)

Form and Size	Notch	Test Temperature, F	Direction	Notched Strength, 10^3 psi	NS/YS Ratio	NS/TS Ratio	Heat	Reference
			18Ni (300) Grade (Continued)					
Bar, 0.75" dia.	K_t = 6.25	RT	L	389	1.36	1.33	06461[l]	23
		-100	L	393	1.28	1.25		
		600	L	348	1.51	1.42		
		900	L	318	1.60	1.47		
Bar	K_t = 12	RT	L	410	1.52	1.49	7C056[m]	5
Bar	K_t = 12	RT	L	401	1.27	1.26	7C057[n]	5
Plate, 0.360"	Dia. = 0.225", 0.001" r.r.	RT	--	281	--	--	23831[k]	16
Forging S, 4"-6" dia.	K_t = 6.3	RT	L	206	0.75	0.73	23992-2[o]	37
Forging W, 5.5" dia.	K_t = 6.3	RT	L	312	1.12	1.08	23992-2	37
		RT	ST	255	0.93	0.89		
Forging P, 5.5" dia.	K_t = 6.3	RT	L	341	1.27	1.22	24178-2[p]	37
		RT	ST	242	0.88	0.85		
Forging O, 5.5" dia.	K_t = 6.3	RT	L	307	1.11	1.08	24178-2	37
		RT	ST	217	0.81	0.78		
Billet, 9" RCS	K_t = 6.3	RT	T	176	0.615	0.60	--	37
Forging, front dome	K_t = 11[e]	RT	Radial	387	--	1.32	C-40148[q]	14
		RT	Tangential	374	--	1.27		
		RT	Axial	264	--	0.91		
Forging, rear dome	K_t = 11[e]	RT	Radial	382	--	1.33	C-40148	14
		RT	Tangential	388	--	1.34		

Footnotes appear on following page.

Footnotes for Table A-32:

Note: r.r. = Root radius of notch.

(a) Specimens had 60 degree V-notches with 0.001-inch root radii and d/D of 0.707.

(b) Major diameter 0.505 in., minor diameter of 60-degree-notch 0.375 in., fatigue cracked to produce about 0.355-in. diameter.

(c) Specimens had 60-degree notch, notch root radius of 0.001 in., and d/D of 0.707.

(d) Notches in specimens had root radii of 0.0031 inch and diameters (d) of 0.176 inch.

(e) Specimens were 0.250-inch diameter, and notch root radii were 0.0005 inch.

	Heat	Ni	Co	Mo	Ti	
(f)	23560 (VAR)	18.72	7.87	4.59	0.24	
(g)	84625 (VAR)	18.9	8.43	4.77	0.30	
(h)	23832 (VAR)	18.34	7.69	5.20	0.45	
(i)	06759 (VAR)	18.20	7.22	4.78	0.50	
(j)	Code C (VAR)	17.6	7.3	4.8	0.50	Carbide-type stringers in these specimens.
(k)	23831 (VAR)	18.20	9.05	4.84	0.69	(18.61Ni, 9.05Co, 5.00Mo, 0.71Ti[16])
(l)	06461 (VAR)	18.77	8.98	4.88	0.77	
(m)	7C056 (VAR)	Low side of composition range.				
(n)	7C057 (VAR)	High side of composition range.				
(o)	23992-2 (VAR)	19.24	8.36	4.84	0.63	Forging S overheated during forging.
(p)	24178-2	19.00	8.57	5.30	0.61	
(q)	C40148	19.08	8.59	4.80	0.60	

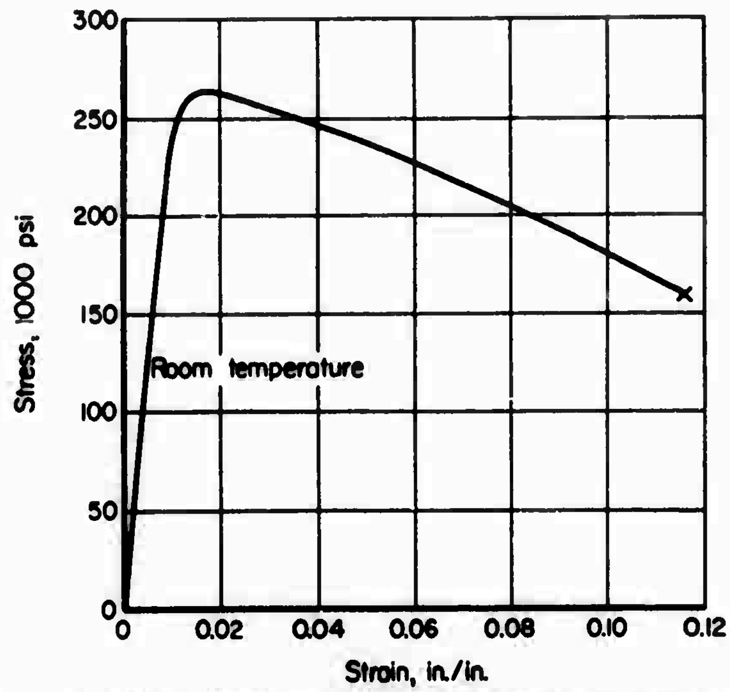

FIGURE A-1. COMPLETE STRESS-STRAIN CURVE FOR 18Ni (250) MARAGING STEEL (AVERAGE) FOR SPECIMENS ANNEALED AT 1500 F, AIR COOLED, AND AGED AT 900 F FOR 3 HOURS(53)

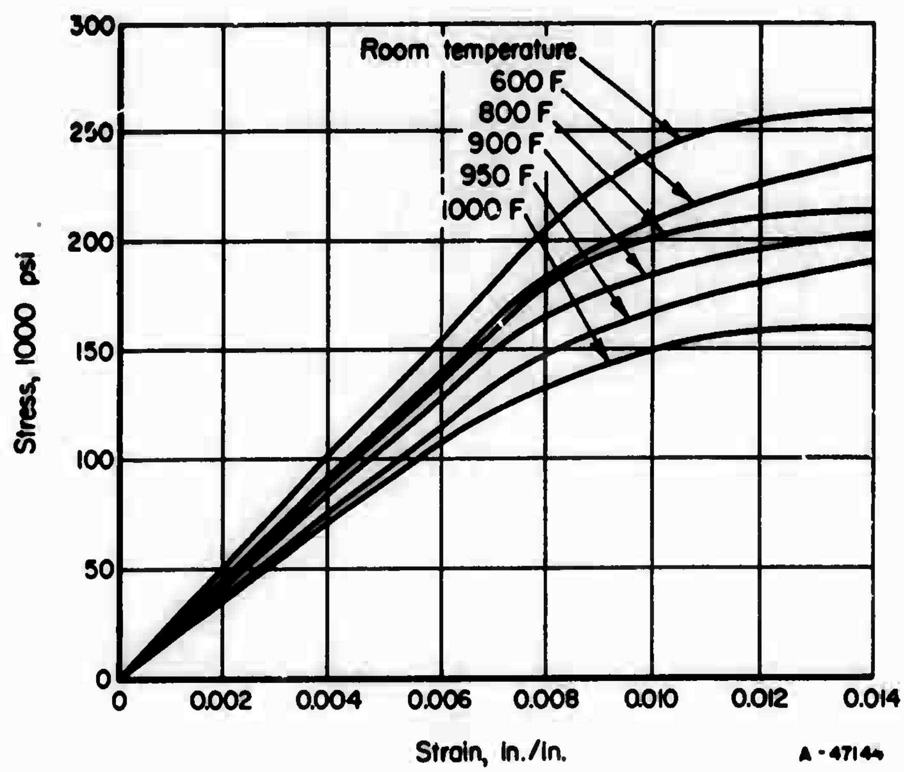

FIGURE A-2. STRESS-STRAIN CURVES FOR 18Ni (250) MARAGING STEEL AT ROOM AND ELEVATED TEMPERATURES FOR SPECIMENS ANNEALED AT 1500 F, AIR COOLED, AND AGED AT 900 F FOR 3 HOURS(53)

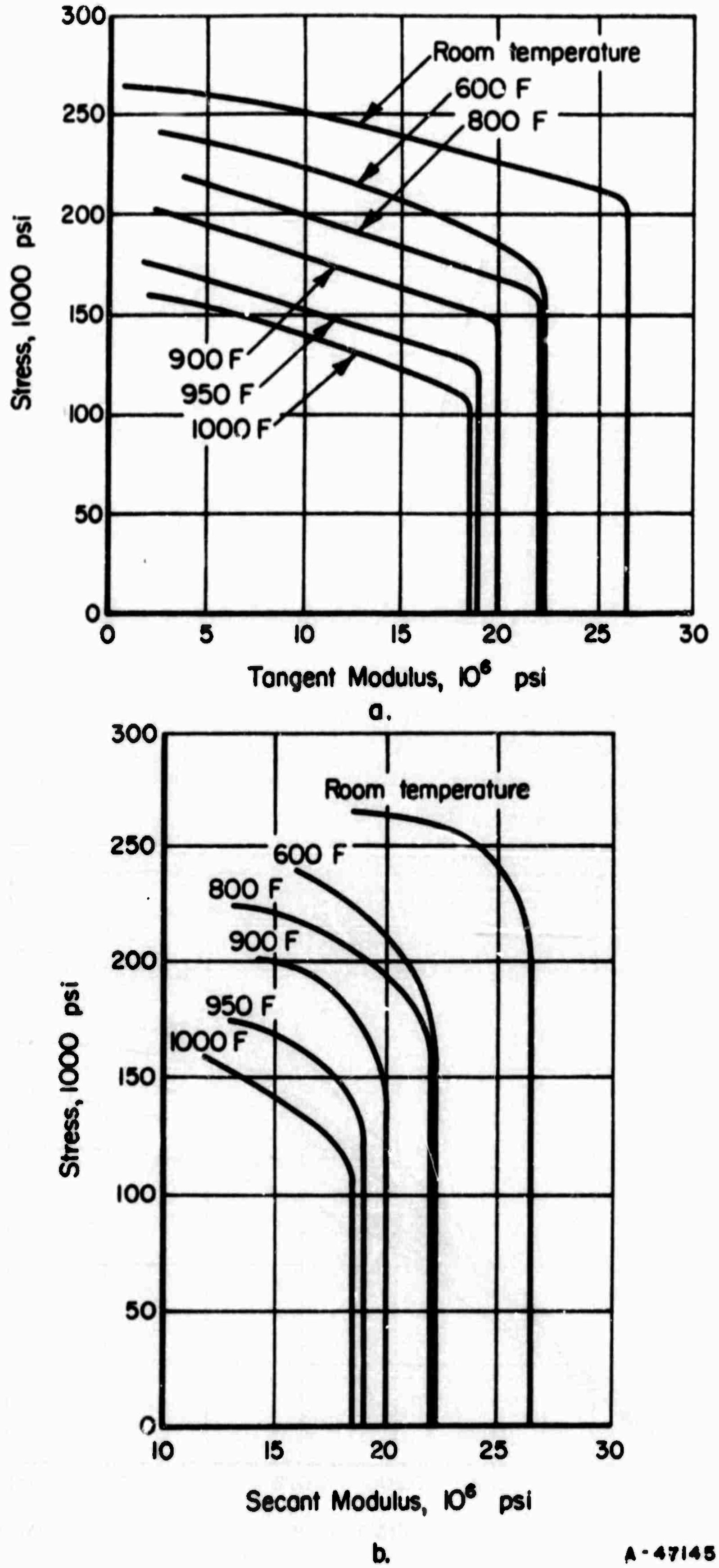

FIGURE A-3. TANGENT AND SECANT MODULUS CURVES AT ROOM AND ELEVATED TEMPERATURES FOR 18Ni (250) MARAGING STEEL TREATED TO A TENSILE STRENGTH OF 265,000 PSI(53)

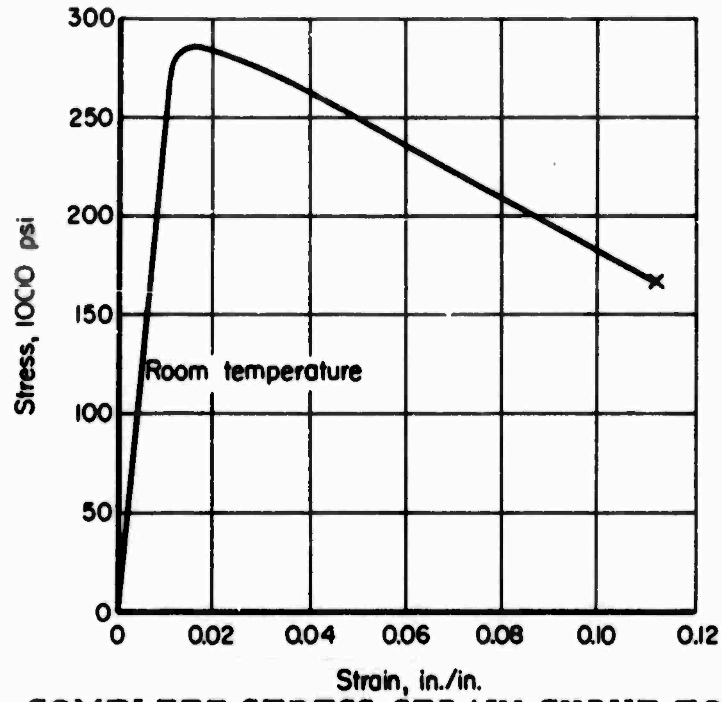

FIGURE A-4. COMPLETE STRESS-STRAIN CURVE FOR 18Ni (300) MARAGING STEEL (AVERAGE) FOR SPECIMENS ANNEALED AT 1500 F, AIR COOLED, AND AGED AT 900 F FOR 3 HOURS[53]

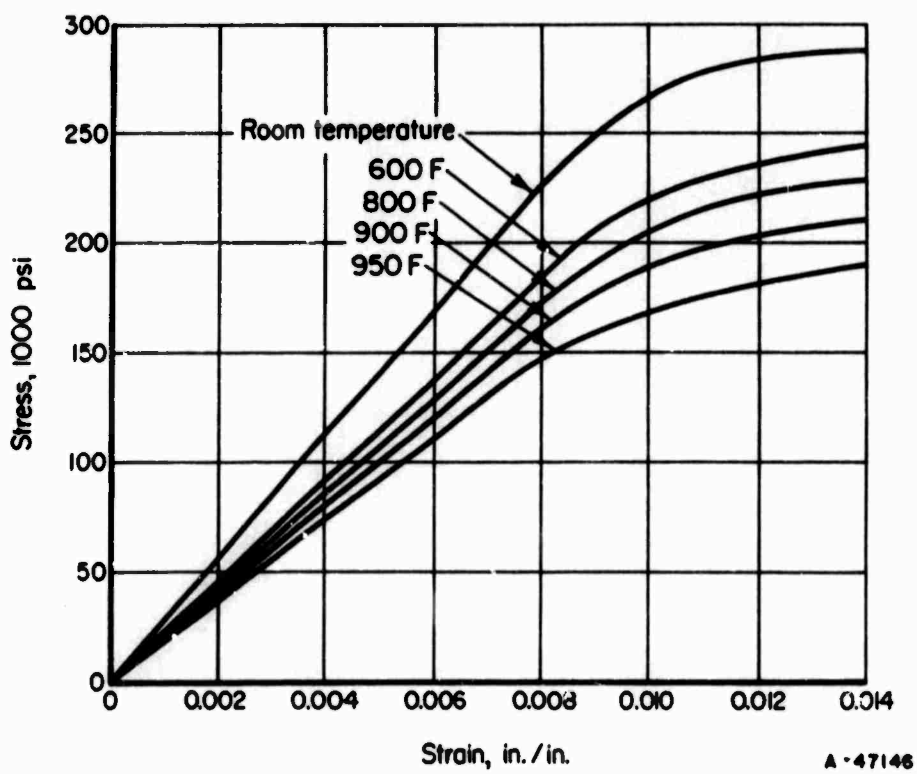

FIGURE A-5. STRESS-STRAIN CURVES FOR 18Ni (300) MARAGING STEEL AT ROOM AND ELEVATED TEMPERATURES FOR SPECIMENS ANNEALED AT 1500 F, AIR COOLED, AND AGED AT 900 F FOR 3 HOURS[53]

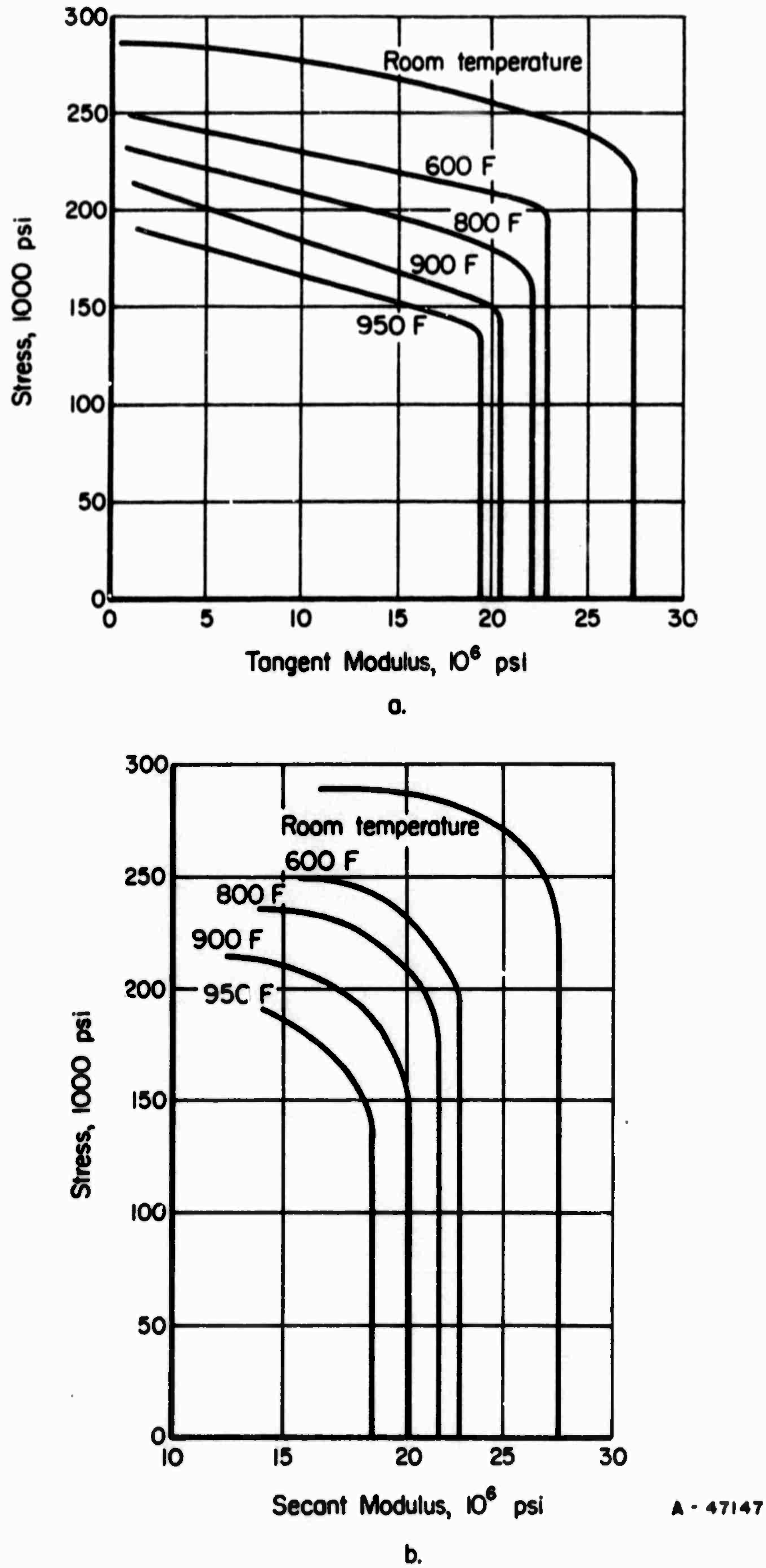

FIGURE A-6. TANGENT AND SECANT MODULUS CURVES AT ROOM AND ELEVATED TEMPERATURES FOR 18Ni (300) MARAGING STEEL HEAT TREATED TO A TENSILE STRENGTH OF 295,000 PSI(53)

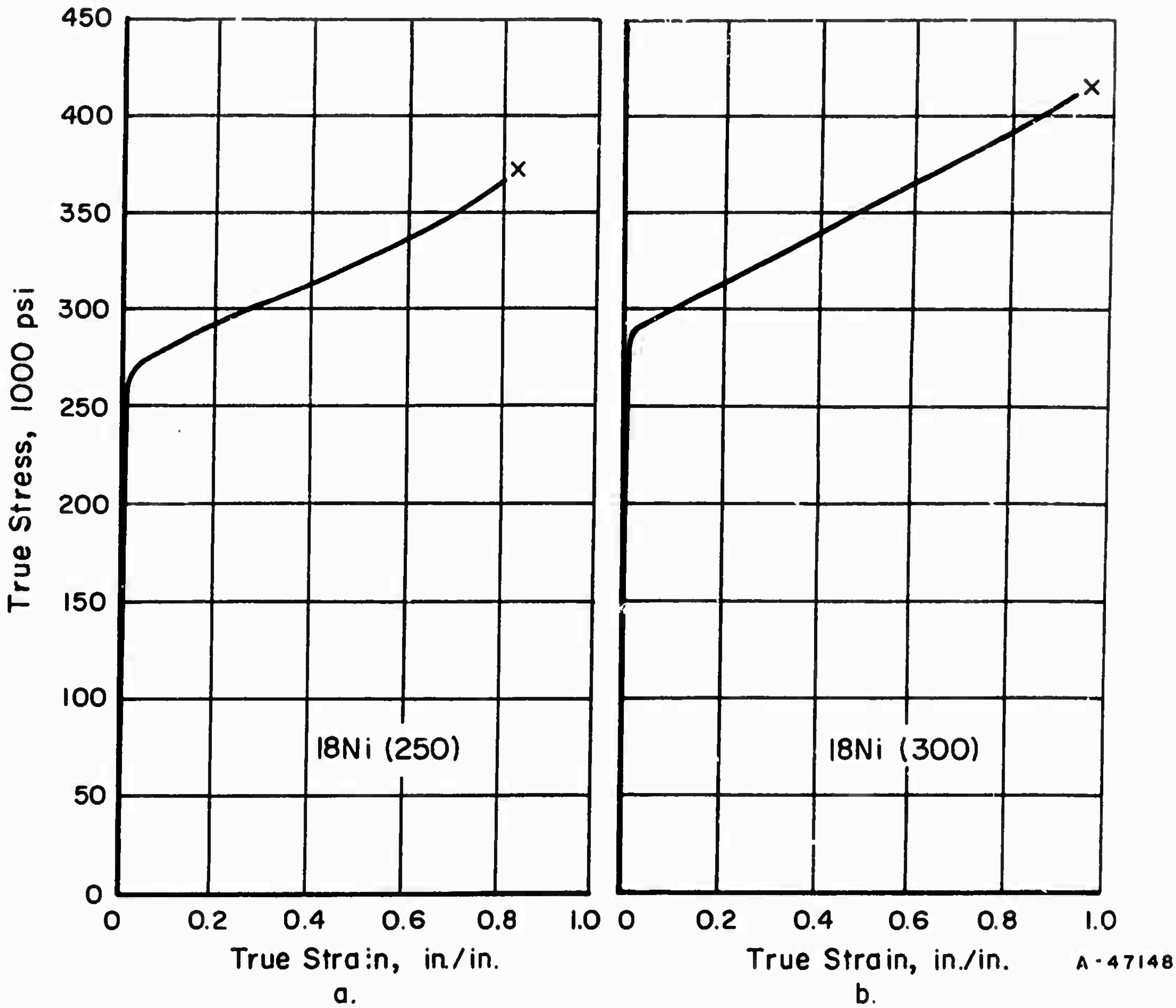

FIGURE A-7. TRUE STRESS-TPUE STRAIN CURVES FOR 18Ni (250) AND 18Ni (300) MARAGING STEELS (AVERAGES) FOR SPECIMENS ANNEALED AT 1500 F, AIR COOLED, AND AGED AT 900 F FOR 3 HOURS

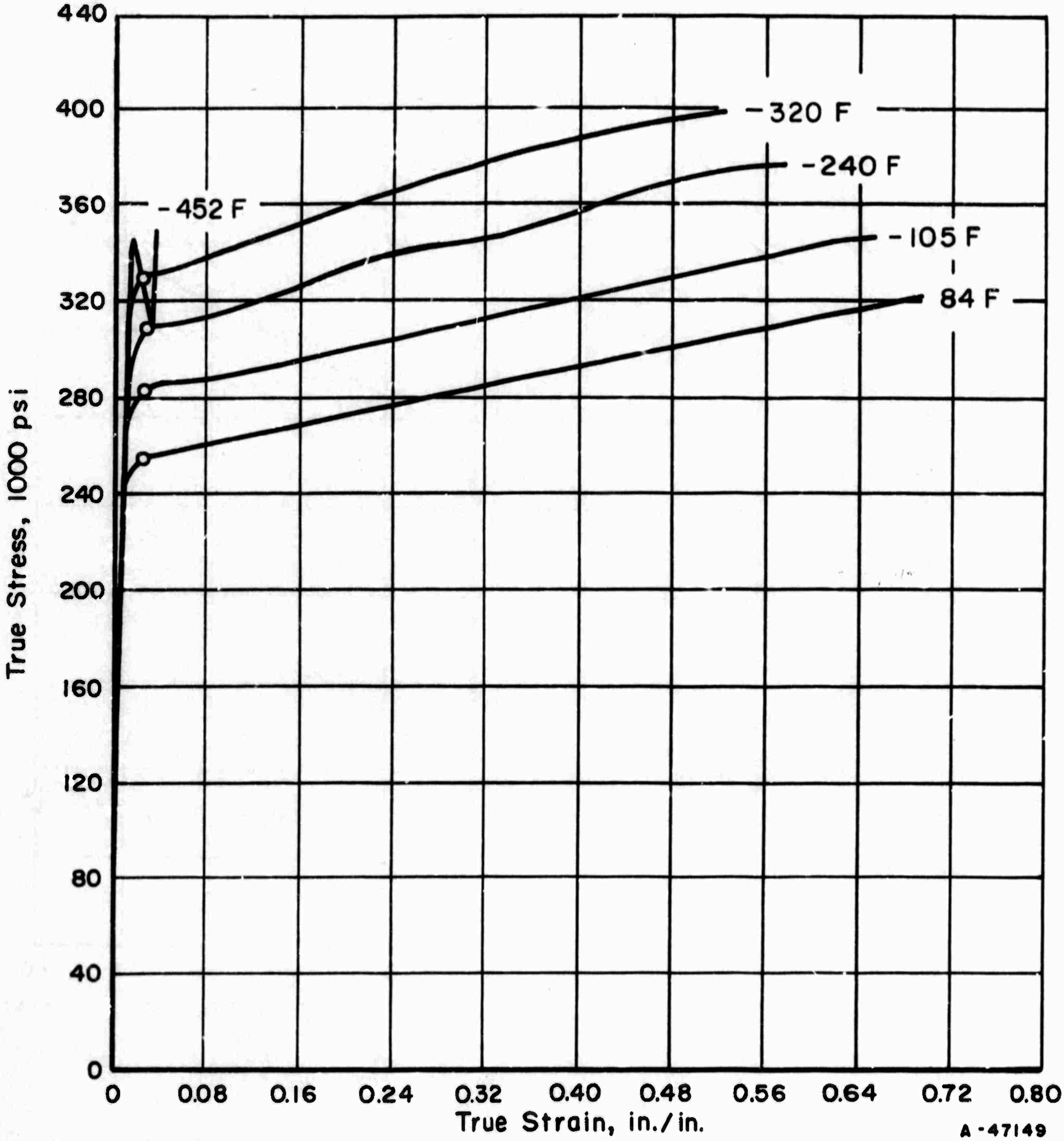

FIGURE A-8. TRUE STRESS-TRUE STRAIN CURVES AT ROOM TEMPERATURE AND LOW TEMPERATURE FOR 18Ni (250) MARAGING STEEL ANNEALED AT 1500 F, AIR COOLED, AND AGED AT 900 F FOR 3 HOURS(12)

Heat A, 1/2 inch plate, 0.02 C, 0.07 Mn, 0.004 P, 0.009 S, 0.09 Si, 18.39 Ni, 7.83 Co, 4.82 Mo, 0.35 Ti, and 0.07 Al.

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